MACARENA SAN MARTIN RUIZ

Recycling of coffee by-products by composting in context of climate-relevant emissions and products

Stuttgarter Berichte zur Abfallwirtschaft Band 141

Forschungs- und Entwicklungsinstitut für
Industrie- und Siedlungswasserwirtschaft sowie
Abfallwirtschaft e.V. in Stuttgart (FEI)

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Impressum

Bibliographische Information der Deutschen Bibliothek

Die Deutsche Bibliothek verzeichnet die Publikation in der Deutschen Nationalbibliographie; detaillierte bibliographische Daten sind im Internet über http://dnb.ddb.de abrufbar.

D 93, Dissertationen der Universität Stuttgart

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Erschienen in der Reihe

Stuttgarter Berichte zur Abfallwirtschaft, Band **141/2023**

Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart

Umschlag, **Buchgestaltung**

Andreas Sihler, Macarena San Martin Ruiz

Verlag

FEI e.V. Eigenverlag, c/o Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft

Bandtäle 2, 70569 Stuttgart

Druck

e.kurz+co druck und medientechnik gmbh, Kernerstraße 5, 70182 Stuttgart

Recycling of coffee by-products by composting in context of climate-relevant emissions and products

Von der Fakultät für Bau- und Umweltingenieurwissenschaften der Universität Stuttgart

zur Erlangung der Würde eine Doktor-Ingenieurin (Dr.-Ing.) genehmigte Abhandlung

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Tag der mündlichen Prüfung: 17.05.2023

Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft

der Universität Stuttgart

Stuttgart, 2023

Foreword

Coffee is one of the most economically important products from tropical countries. Inadequate treatment of the residues resulting from coffee production and improper use of fertilizers lead to significant climate-relevant emissions such as methane and nitrous oxide. This is particularly true of coffee plantations in Costa Rica, which account for about a quarter of the country's agricultural greenhouse gas emissions. On these coffee plantations, the majority of the coffee by-products generated during coffee production, especially the coffee pulp, are disposed of as waste by dumping.

By treating coffee by-products aerobically through composting, the compost produced can return nutrients to plantations and improve soils. At the same time, emissions of climate-relevant gases (especially methane) can be significantly reduced compared to anaerobic deposition if an aerobic rotting process can be ensured. With regard to climate relevance, emissions of nitrous oxide during the application of mineral fertilizers or their substitution by composts in the plantations must also be considered.

With this dissertation, Dr.-Ing. Macarena San Martin Ruiz takes up these highly topical issues. The author has systematically investigated scientifically, on the basis of pilot-scale experiments through to field experiments on a technical scale in Costa Rica, which methane emissions occur with the currently practiced treatment method of the coffee by-products and how emissions can be significantly reduced by an optimized composting process with structural materials and how the resulting composts can be reused in the coffee plantations in the sense of a circular economy. Furthermore, the nitrous oxide emissions, which have a high climate relevance, were investigated when using composts in comparison to mineral fertilizers on coffee plantations.

The results on methane emissions from the treatment of coffee by-products, which can be scientifically substantiated for the first time on this scale, show that a reduction in CO_2 equivalents of approx. 90 % is possible by composting these residues with structural material compared to the mono-composting of coffee pulp practiced to date; compared to the anaerobic deposition also currently practiced, even by more than 98 %. Likewise, based on the systematic investigations, it can be shown that the nitrous oxide emissions can be reduced by approx. 50 % when using the composts produced in comparison to mineral fertilizers on the plantations.

The findings obtained from the dissertation are of great importance not only for science, but especially for practice. This will enable the coffee industry to significantly reduce greenhouse gas emissions and make coffee production more sustainable by composting coffee by-products and applying the compost.

I wish this important dissertation a wide recognition and dissemination among international experts in this field.

Stuttgart, June 2023 Prof. Dr.-Ing. Martin Kranert

Acknowledgments

First and foremost, I'd like to thank my supervisor, Professor Dr.Ing-Martin Kranert, and my co-supervisor, Dr.Ing-Martin Reiser, for their help with the proposal and the PhD conduct research. I'd also like to thank them both for providing me with the incredible opportunity to write this thesis. I'd like to thank the Mill Coopetarrazu R.L personnel, particularly Carlos Vargas, Jimmy Porras, Maria Jose Naranjo, Paul Cascante, and the CEDAO department personnel, for great and productive field trips and lab work, as well as for always being committed and very helpful with any possible issue related to daily work in the Costa Rican fields. I'd like to express my gratitude to Prof. Dr. Tiziano Zarra for serving as my thesis co-reporter and for giving me helpful feedback during the last steps of my thesis.

Thank you to all current and former colleagues for your valuable contributions, vibrant debates, and (at times, much-needed) social breaks. Special thanks to Hildemar, Veronica, and Benjamin for their assistance in making the PhD lab work environment enjoyable. Many thanks to my students Jorge and Salua for their valuable contributions and discoveries during the research, as well as their laboratory assistances.

Dr. rer. nat. Bertram Kuch deserves special recognition for his endless discussions and insightful comments on my PhD thesis and research. Also, for his encouragement, motivation, and offer of space in his department and laboratory to conduct part of the experiments.

Last but not least, I'd like to express my gratitude Paul, my mother, my family and to my friends (you know who you are), who supported me throughout the PhD project and gave me the reassurance I needed to succeed.

Macarena San Martin Ruiz May 2023

Acknowledgments

***Thank a coffee farmer if you drank coffee today. Dedicated to each and every one of them*.**

Acknowledgments

“The story of the hummingbird is about this huge forest being consumed by a fire. All the animals in the forest come out and they are transfixed as they watch the forest burning and they feel very overwhelmed, very powerless, except this little hummingbird. It says, ‘I’m going to do something about the fire!’ So it flies to the nearest stream and takes a drop of water. It puts it on the fire, and goes up and down, up and down, up and down, as fast as it can.

In the meantime all the other animals are saying to the hummingbird, ‘What do you think you can do? You are too little. This fire is too big. Your wings are too little and your beak is so small that you can only bring a small drop of water at a time.’

But as they continue to discourage it, it turns to them without wasting any time and it tells them, ‘I am doing the best I can”

“I will be a hummingbird; I will do the best I can"

Kenyan environmental activist, women’s rights advocate, and 2004 Nobel Peace Prize Laureate Professor Wangari Maathai

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Abbreviations and acronyms

AAS	Atomic Absorption Spectroscopy
ANOVA	Analysis of variance
BGK	Bundesgütegemeinschaft Kompost
C/N	Carbon to nitrogen ratio
CEC	Cation exchange capacity
CEDAO	Research Center for the Development of Organic Alternatives
CH	Coffee Husk
CICE	Effective Cation Exchange Capacity
CO_{2eq}	Carbon dioxide equivalent
COP	United Nations Climate Change Conference
CP	Coffee Pulp
CSA	Climate-Smart Agriculture
DM	Dry Mass
DS	Dry solids
DW	Dry Weight Basis
EC	Electrical conductivity
EF	Emission factor
ER	Emission rate
F1	Fertilization 1
F2	Fertilization 2
FAO	Food And Agriculture Organization
FIA	Flow injection analyzer
FM	Fresh mass
FONAFIFO	National Forestry Finance Fund
FTIR	Fourier-transform infrared spectroscopy
GHG	Greenhouse Gas
GW	Green waste

GWP	Global Warming Potential
HSD	Honestly significant difference
ICAFE	Coffee Institute of Costa Rica / Costa Rican Coffee Institute
IMN	Meteorological Institute of Costa Rica
INTA	Agricultural Technology Transfer Institute
IRWM	Multilevel Commission for Integrated Waste Management
MC	Moisture content
MINAE	Ministry of Environment and Energy Of Costa Rica
N	North
NAMA	Nationally, Appropriate, Mitigation Actions
PC	Plant compatibility (relative yield)
pH	Negative logarithm of the hydrogen ion (H^+) activity
PRESOL	Costa Rica Solid Waste National Plan
PVC	Polyvinylchloride
SA	Soil amendment (compost)
SC	Spent Coffee
SD	Standard Deviation
SDGs	Sustainable Development Goals
SNF	Nitrogen fertilizer
SS	Silver Skin
TC	Control (current compost treatment at the mill)
UNFCCC	United Nations Framework Convention on Climate Change
VS	Volatile Solids
W	West
WC	Water Content
ƿt	Bulk density
κ	Electrical conductivity

Units

%	Percent
°C	Degree Celsius
CFU	Colony-forming units
cm	Centimeter
d	Day
g	Gram
h	Hour
ha	Hectare
kg	Kilogram
km	Kilometer
km^2	Square kilometer
L	Liter
m	Meter
m.a.s.l.	Meters above sea level
m^2	Square meter
m^3	Cubic meter
Mg	Megagram
mg	Milligram
mS	Millisiemens
t	Ton (metric unit)
vol%	Volume percent
yr	Year

Chemical Compounds

C	Carbon
B	Boron
Ca	Calcium
CO_2	Carbon Dioxide
Cu	Copper
Fe	Iron
$H_2PO_4^-$	Orthophosphate
K	Potassium
K_2O	Potassium oxide
Mg	Magnesium
MgO	Magnesium oxide
Mn	Manganese
N	Nitrogen
N_2O	Nitrous Oxide
NH_3^-	Ammonia
NH_4^+	Ammonium
NO	Nitric oxide
NO_2^-	Nitrite
NO_3^-	Nitrate
O_2	Oxygen
PO_4^{3-}	Phosphate
P	Phosphorus
P_2O_5	Phosphorus pentoxide
S_2^-	Sulfur
Zn	Zinc

Summary

Coffee has become one of the most popular beverages and provides a livelihood for millions of people around the world. Coffee is one of Costa Rica's most important and emblematic exports (about one and a half million bags per year) and is closely linked to the country's national identity. However, climate change poses a challenge to the livelihoods of Costa Rican coffee farmers and the long-term viability of the crop. Thus, the environmental impact of coffee production must also be reduced and made more sustainable. Therefore, it is necessary to treat the residues from coffee production as climate-neutral and resource-saving as possible in the sense of a circular economy. This is of particular importance, not least because the consumption of coffee has increased worldwide.

Agriculture and waste management are disconnected from each other worldwide. This leads to permanent nutrient depletion of soils and high greenhouse gas (GHG) emissions due to insufficient or excessive use of fertilizers. Coffee by-products, especially coffee pulp, are usually considered waste on coffee plantations and are mostly discarded or disposed of in rivers. In some cases, composting of residues also takes place, which usually results in high emissions due to improper rotting processes. In the context of global warming, inadequate composting and mineral fertilization contribute to greenhouse gas emissions. Composting emits greenhouse gases such as methane from the decomposition of organic material and carbon dioxide from fossil fuels from the equipment required to turn and process the waste. Fertilization of coffee plants, on the other hand, emits greenhouse gases such as nitrous oxide from the soil, especially when nitrogen fertilizers are used. This leads to serious consequences for the climate and the environment.

The purpose of the present thesis was to investigate which methane emissions occur with the current treatment method of the residues and how an optimized composting process can significantly reduce these emissions and at the same time produce an organic fertilizer. In addition, nitrous oxide emissions from the use of composts compared to mineral fertilizers on coffee plantations should be investigated. This should contribute to making coffee production more sustainable.

Summary

The field trials were conducted at the coffee plantation of CoopeTarrazú R.L. Mill (San Marcos de Tarrazú, San José, Costa Rica), which is the largest coffee cooperative in the country.

The composting research was first conducted on a laboratory scale and then implemented on a pilot scale at a composting facility in Germany. Based on this, the field trials were carried out at the CoopeTarrazú R.L facilities at semi-industrial and industrial scale.

Using different structural materials (especially green waste) and different material mixtures, the material-specific parameters of the rotting material and the rotting process were investigated and the resulting composts were evaluated. These were, in particular, water content, loss on ignition, pH, C/N ratio, density, and temperature profile and the effects on the degree of rotting, stability, and plant compatibility of the compost product. A central component was the measurement of methane emissions. This was done using gas hoods and gas analysis by Fourier Transform Infrared Spectroscopy (FTIR). A portable gas detector was used to determine CH_4 gas concentrations for field tests at the composting facility in Costa Rica.

Since N_2O is a significant greenhouse gas in agriculture, a strategy to measure it was developed. First, field experiments with synthetic nitrogen fertilizer and compost were conducted in a botanical garden in Germany (Wilhelma, Stuttgart), then in the coffee plantations of CoopeTarrazú R.L. in Costa Rica. N_2O emission rates in the experimental fields were measured by FTIR to determine N_2O levels in the coffee plantations during the coffee fertilization cycle and the effects of the types of fertilizers and composts used in the coffee plantations.

Methane emission rates in laboratory experiments and pilot trials at the composting plant ranged from 0.007 to 3.1 g x m^{-2} x h^{-1}. Results of measurements of the composting process based on this in field trials in Costa Rica ranged from 1.6 to 38 g x m^{-2} x h^{-1}. The lowest emission rates were found at a structural material content of 50%. They were the equivalent of 11.6 g CH_4/kg coffee pulp.

Compared to the composting of coffee pulp without structural material, in which approx. 0.4 kg CO_{2eq} are released in relation to 1 kg green coffee, this value was reduced to 0.04 kg CO_{2eq} when structural material was used. A reduction in climate-relevant CH_4 emissions of up to approx. 90% could thus be achieved. In contrast, the value for deposition in the field is approx.

2.1 kg kg CO_{2eq}; this corresponds to approx. half of the emissions in the coffee production process (approx. 4 kg CO_{2eq}).

Nitrous oxide emission rates from fertilization ranged from 0.1 to 0.25 g x m^{-2} x h^{-1} in 2019 and 0.3 to 0.5 g x m^{-2} x h^{-1}in 2020, showing clear correlation between fertilizer, fertilization period, and N_2O emissions. Here, emissions were significantly lower when composts were used compared to mineral fertilizers. The CO_2 footprint related to 1 kg green coffee was 1.88 kg CO_{2eq} when compost was applied, and significantly higher at 3.5 kg CO_{2eq} when mineral fertilizers were applied.

In summary, it can be shown in the present thesis that a significant reduction of greenhouse gas emissions is possible through the professional composting of residues from coffee production, and at the same time an organic fertilizer can be produced that can be reused in the coffee plantations. Emission factors for N_2O were determined for the use of composts compared to mineral fertilizers in coffee production, showing a significant advantage in terms of emissions when using composts.

The findings of the research can help to improve the treatment of residues in coffee production and enable low-emission composting, particularly regarding methane emissions. The resulting compost can be reused in coffee plantations, thereby saving on mineral fertilizers. This also leads to a significant reduction in nitrous oxide emissions. This makes it possible for coffee producers to implement climate protection concepts and reduce their carbon footprint.

Kurzfassung

Kaffee ist zu einem der beliebtesten Getränke geworden und sichert Millionen von Menschen auf der ganzen Welt den Lebensunterhalt. Kaffee ist eines der wichtigsten und symbolträchtigsten Exportgüter Costa Ricas (etwa eineinhalb Millionen Säcke pro Jahr) und eng mit der nationalen Identität des Landes verbunden. Der Klimawandel stellt jedoch eine Herausforderung für den Lebensunterhalt der costaricanischen Kaffeebauern und die langfristige Überlebensfähigkeit der Pflanze dar. So müssen auch die Umweltauswirkungen bei der Kaffeeproduktion reduziert und diese nachhaltiger gestaltet werden. Daher, ist es erforderlich, besonders auch die Rückstände aus der Kaffeeproduktion möglichst klimaneutral und ressourcenschonend im Sinne einer Kreislaufwirtschaft zu behandeln. Dies ist nicht zuletzt von besonderer Bedeutung, da der Konsum von Kaffee weltweit zugenommen hat.

Land- und Abfallwirtschaft sind weltweit voneinander entkoppelt. Dies führt zu permanentem Nährstoffentzug der Böden und hohen Treibhausgasemissionen (THG) durch unzureichenden oder exzessiven Einsatz von Düngemitteln. Kaffeenebenprodukte, besonders Kaffeefruchtfleisch, werden auf Kaffeeplantagen üblicherweise als Abfall angesehen und meist weggeworfen oder in Flüssen entsorgt. Teilweise findet auch eine Kompostierung der Rückstände statt, die in der Regel durch unsachgemäße Rotteprozesse zu hohen Emissionen führt. Im Zusammenhang mit der globalen Erwärmung tragen unzureichende Kompostierung und mineralische Düngung zu Treibhausgasemissionen bei. Bei der Kompostierung werden Treibhausgase wie Methan durch den Abbau von organischem Material und Kohlenstoffdioxid aus fossilen Energieträgern durch die zum Umsetzen und Verarbeiten der Abfälle erforderlichen Geräte emittiert. Bei der Düngung von Kaffeepflanzen hingegen werden Treibhausgase wie Lachgas aus dem Boden emittiert, insbesondere wenn Stickstoffdünger verwendet werden. Dies führt zu ernsthaften Konsequenzen für Klima und Umwelt.

Gegenstand der vorliegenden Arbeit war zu untersuchen, welche Methanemissionen bei der derzeitigen Behandlungsmethode der Rückstände auftreten und wie durch einen optimierten Kompostierungsprozess diese Emissionen signifikant reduziert werden können und gleichzeitig ein organischer Dünger hergestellt werden kann. Darüber hinaus sollten die Lachgasemissionen beim Einsatz von Komposten im Vergleich zu Mineraldüngern auf den Kaffeeplantagen untersucht werden. Damit soll ein Beitrag geleistet werden, die Kaffeeproduktion nachhaltiger zu gestalten.

Die Feldversuche wurden auf der Kaffeeplantage der CoopeTarrazú R.L. Mill (San Marcos de Tarrazú, San José, Costa Rica), welche die größte Kaffeecooperative des Landes ist, durchgeführt.

Die Forschungsarbeiten zur Kompostierung wurden zunächst im Labormaßstab durchgeführt und dann im Pilotmaßstab in einer Kompostierungsanlage in Deutschland umgesetzt. Hierauf aufbauend wurden die Feldversuche auf den Anlagen der CoopeTarrazú R.L im halbtechnischen und großtechnischen Maßstab durchgeführt.

Unter Einsatz verschiedener Strukturmaterialien (besonders Grünabfälle) und verschiedenen Materialmischungen wurden die materialspezifischen Parameter des Rottegutes und des Rotteprozesses untersucht und die entstandenen Komposte bewertet. Dies waren insbesondere Wassergehalt, Glühverlust, pH-Wert, C/N-Verhältnis, Dichte, und Temperaturverlauf und die Auswirkungen auf den Rottegrad, Stabilität und Pflanzenverträglichkeit des Kompostprodukts. Ein zentraler Bestandteil war die Messung der Methanemissionen. Diese erfolgte über Gashauben und Gasanalyse durch FTIR-Spektroskopie (Fourier Transform Infrared Spectroscopy). Für Feldversuche auf der Kompostierungsanlage in Costa Rica wurde ein tragbarer Gasdetektor zur Ermittlung der CH_4 Gaskonzentration eingesetzt.

Da N_2O ein signifikantes Treibhausgas in der Landwirtschaft darstellt, wurde eine Strategie zu dessen Messung entwickelt. Zunächst wurden in einem botanischen Garten in Deutschland (Wilhelma, Stuttgart), dann auf den Kaffeeplantagen der CoopeTarrazú R.L. in Costa Rica, Feldversuche mit synthetischem Stickstoffdünger und Kompost durchgeführt. Die N_2O-Emissionsraten in den Versuchsfeldern wurden mittels FTIR gemessen, um den N_2O-Gehalt in den Kaffeeplantagen während des Kaffee-Düngungszyklus sowie die Auswirkungen der in den Kaffeeplantagen verwendeten Düngemitteltypen und Komposte zu ermitteln.

Die Methanemissionsraten in den Laborexperimenten und den Pilotversuchen im Kompostwerk lagen zwischen 0,007 bis 3,1 g x m^{-2} x h^{-1}. Ergebnisse der darauf aufbauenden Messungen des Kompostierprozesses in Felduntersuchungen in Costa Rica schwankten zwischen 1,6 und 38 g x m^{-2} x h^{-1}. Bei einem Strukturmaterialanteil von 50 % wurden die geringsten Emissionswerte gefunden. Sie lagen umgerechnet bei 11,6 g CH_4/kg Kaffeepulpe.

Im Vergleich zur Kompostierung von Kaffeepulpe ohne Strukturmaterial, bei der bezogen auf 1 kg Rohkaffee ca. 0,4 kg CO_2eq freigesetzt werden, konnte beim Einsatz von Strukturmaterial dieser Wert auf 0,04 kg CO_2eq verringert werden. Damit konnte eine Reduktion der klimarelevanten CH_4-Emissionen um bis zu ca. 90 % erreicht werden. Demgegenüber liegt der Wert bei Ablagerung auf dem Feld bei ca. 2,1 kg CO_2eq; dies entspricht ca. der Hälfte der Emissionen beim Produktionsprozess von Kaffee (ca. 4 kg CO_2eq).

Die von der Düngung ausgehenden Lachgasemissionensraten betrugen zwischen 0,1 bis 0,25 g x m^{-2} x h^{-1} im Jahre 2019 und 0,3 bis 0,5 g x m^{-2} x h^{-1} im Jahre 2020. Es zeigt sich deutlicher Zusammenhang zwischen Düngemittel, Düngeperiode und N_2O Emissionen. Hierbei waren die Emissionen beim Einsatz von Komposten im Vergleich zu Mineraldüngern deutlich geringer. Der CO_2-Fußabdruck lag bezogen auf 1 kg Rohkaffee bei der Anwendung von Kompost bei 1,88 kg CO_2eq, bei der Anwendung von Mineraldüngern deutlich höher bei 3,5 kg CO_2eq.

Zusammengefasst kann in der vorliegenden Arbeit gezeigt werden, dass durch die fachgerechte Kompostierung von Rückständen aus der Kaffeeproduktion eine signifikante Reduktion von Treibhausgasemissionen möglich ist und gleichzeitig ein organischer Dünger erzeugt werden kann, der in den Kaffeeplantagen wiedereingesetzt werden kann. Für den Einsatz von Komposten im Vergleich zu Mineraldüngern bei der Kaffeeproduktion wurden Emissionsfaktoren für N_2O ermittelt, die einen deutlichen Vorteil hinsichtlich der Emissionen beim Einsatz von Komposten zeigen.

Die Forschungsergebnisse können dazu beitragen, die Behandlung von Rückständen bei der Kaffeeproduktion zu verbessern und eine emissionsarme Kompostierung besonders im Hinblick auf die Methanemissionen zu ermöglichen. Der entstehende Kompost kann in den Kaffeeplantagen wiedereingesetzt werden und hierbei Mineraldünger eingespart werden. Dies führt gleichzeitig zu einer deutlichen Verringerung an Lachgasemissionen. Damit ist es für die Kaffeeproduzenten möglich, Konzepte zum Klimaschutz umzusetzen und den CO_2-Fußabdruck zu reduzieren.

1. General introduction

1.1. Background

In the coffee industry worldwide, climate change is creating a solid threat due to rising temperatures, more frequent droughts, and heatwaves, threatening a large part of the coffee-producing areas in the next 50 years (Davis et al., 2012). Therefore, actions to increase the climate resilience among the coffee farms and support the coffee sector enhance sustainability, circular economy, and low emissions solutions during the entire coffee chain, especially during the farming and production cycle (Avraamidou et al., 2020). Furthermore, coffee is the most traded tropical good, with up to 25 million farming households producing 80% of global supply. It produces a significant amount of coffee by-products/residues during the entire production cycle, from the fruit to coffee as a beverage (FAO, 2021).

Coffee is a plantation crop belonging to the genus *Coffea* of the family, *Rubiaceae* subfamily *Cinchonoideae* (Ferreira et al., 2019). It takes at least five years for a coffee plant to carry its first harvest period and be productive for about fifteen years (Vaast et al., 2006). Only ripe fruits are harvested by hand from each dominant variety at a specific elevation and stored in a separate independent lot (Buitrago-Osorio et al., 2022, P. S. Murthy & Madhava Naidu, 2011).

Coffee production is divided into two types: Arabica (Coffea arabica) and Robusta (Coffea robusta), where Arabica accounts for roughly 75% of the global output (Dada et al., 2022). Production costs are much higher owing to more stringent demands for soil and climatic conditions, crop management, primary processing, and pest and disease control, including the potentially devastating coffee leaf rust and berry diseases (Hameed et al., 2020). In addition, climate change threatens the sustainability of arabica coffee production—rising temperatures, longer droughts, and excessive rainfall (Cristancho et al., 2012). Furthermore, sustainability is damaged due to the lack of waste management; coffee monocultures discharge emissions and compounds, polluting the environment (Gómez-Salcedo et al., 2021). Therefore, waste management and usage of soil amendments are becoming essential issues among coffee producers to strengthen climate protection. Compost production using coffee by-products is an alternative to the high amounts of waste (Rangarajan & Anne Tharian, 2019). Besides, coffee plantations have significant quantities of chemical pesticides and synthetic fertilizers that contribute to the change of the regular cycles of nature (Gmünder et al., 2020).

Generally, large amounts of nitrogen (N) are applied to coffee plantations during the vegetative phase (from germination to blossoming). As a result, they often exceed the maximum doses required by the plant to ensure that the needs of the plants are adequate. Due to this overdose made in coffee plantations, nitrous oxide (N_2O) emissions increase, depending on the soil N contents, composition, chemical properties, and environmental factors (W.-J. Zhou et al., 2016).

Reducing agricultural emissions, mainly methane and nitrous oxide, is vital to climate change mitigation since agriculture contributes to anthropogenic global warming (Lynch et al., 2021). Methane (CH_4), the second most important greenhouse gas (GHG) after carbon dioxide (CO_2), is responsible for more than a third of total anthropogenic climate forcing (Ramaswamy et al., 2001). CH_4 accounts for 14% of the global GHG, the second most abundant GHG (Cui et al., 2015). On the other hand, N_2O is a significant GHG, and its global warming potential (GWP) is about 310 times more relevant than CO_2 (Rivera et al., 2017).

N_2O reported between 2 – 4% and 44% of the total GWP of GHG (Bernstein et al., 2007). One direct source of N_2O are synthetic fertilizers, which help feed plants by adding nitrogen directly into the soil. Unfortunately, fertilizers also cause intense pressure on the environment and food quality (Golabi et al., 2007; Richter & Roelcke, 2000).

Once the fertilizer is applied, bacteria in the soil use nitrogen to produce the energy needed to live and grow (Ramirez et al., 2010). When the fertilizer is combined with soil conditions favorable for denitrification, large amounts of nitrous oxide can be produced and emitted into the atmosphere (Wang et al., 2020; Xie et al., 2015). Indirect agricultural sources are not defined, but researchers state that the most relevant come from N leaching and runoff from agricultural soils (Nevison, 1998; van der Hoek et al., 2007). In addition, large amounts of nitrogen enter drainage ditches, streams, rivers, and estuaries; another important source is the volatilization and deposition of ammonia from fertilizer applied to crops (Reay et al., 2012).

The biological effect of N fertilizer varies depending on the species but only seeks to obtain the best yield quality during harvest. However, in the long term, continuous fertilization disturbs the balance in the natural process, especially with environmental pollution (eutrophication and N_2O emission) (Xie et al., 2015). Figure 1-1 represents the production system of coffee processing. According to the Coffee Insitute of Costa Rica (ICAFE), the stage starts at the seedbed, where trees are prepared in nursery beds. Once they are ready, they are transplanted to the terraces and hillsides (about a year old and less than 30.48 cm high).

After that, the coffee plants will continue growing for another two to four years before they start producing coffee beans (coffee cherries), called the growth stage. Following this, the coffee plant performs regularly during its lifetime, and during that stage, the coffee plants are fertilized (green images) at least three times per year (Giraldi-Díaz et al., 2018).

The Costa Rican coffee sector mainly uses wet processing, in which the pulp removal is done the same day it is harvested. Once harvested, it enters the coffee processing stage, where the coffee cherries are washed and carried out for de-pulping. Next, the pulp and the mucilage are removed to obtain the coffee bean (el Benni & Reviron, 2009; Sevenster & Verhagen, 2010). Finally, the classification of green coffee, roasting and grinding, if necessary, is made after removing the by-products (blue images) to proceed with the commercialization to produce the final beverage (Mussatto et al., 2011).

The beans are collected and moved to a large fermentation tank. Here, the bacterias and microbes remove the mucilage until the mucilage layer is dissolved (Fitri et al., 2021). Then, the green beans without mucilage are added back to the furnace for the next batch. The beans go through a final quality control step. It is typically used as a vibrating sorter table, where smaller beans with lower quality beans are separated from the big beans that possess the highest quality, separated in different bags to keep the quality of the coffee. Then, the coffee is roasted and ready to pack and ship to different establishments (Chala et al., 2018; Gómez-Salcedo et al., 2021). Coffee has particular growing conditions and is primarily threatened by climate crises (Bianco, 2020). It is predicted that by 2050 the temperature could increase in the main plantation zones, with increased rainfall and increasingly arid dry seasons (Bianco, 2020). With the temperature rise, coffee consumption is increasing worldwide due to changes in habits and the development of emerging economies (IDB, 2022).

To meet demand, coffee will need to be grown on a larger scale, replacing forest land-use and increasing the negative climatic effect (Fitch et al., 2022). Therefore, targeted solutions have been implemented in Costa Rica, promoting sustainable practices, enhancing low emissions production, and waste management to incorporate organic amendments in the coffee plantations (GIZ, 2021).

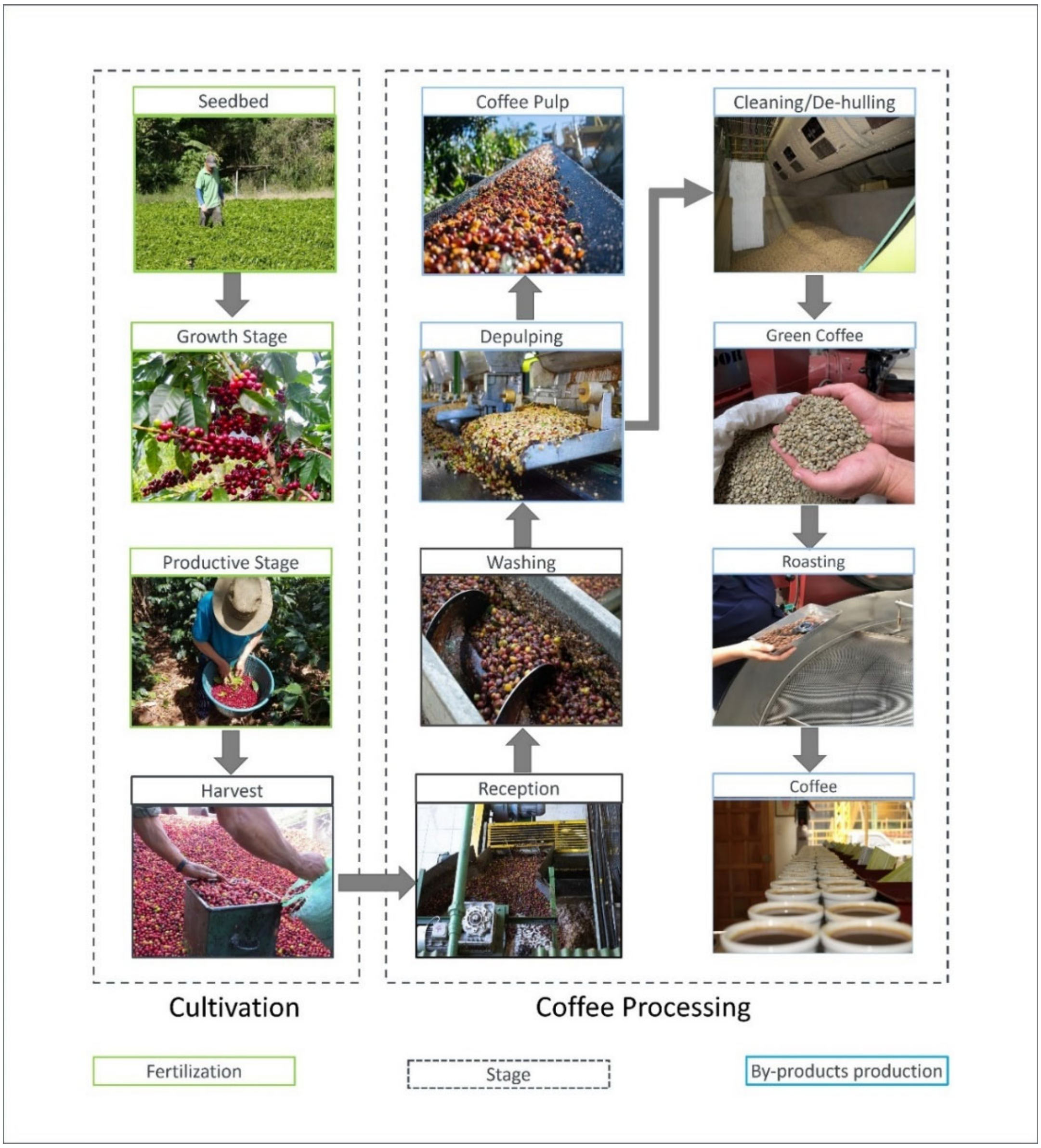

Figure 1 - 1: Coffee cultivation and processing diagram.

1.2. Status Quo

The production of coffee in Costa Rica is divided into seven main regions where coffee arabica is produced (figure 1 - 2) (ICAFE, 2015; Sustaincoffee, 2022). Each region possesses differences such as relative humidity and elevation. Zones are distributed in low country zones (below 1000 m.a.s.l). In this zone, the coffee is softer; on the other hand, there are high zones (1.200 m.a.s.l) mainly of volcanic origin, and thus, the coffee is stronger or more acidic (ICAFE, 2017). Coffee marketing is in the hands of the private sector; however, the state maintains supervision and control through ICAFE. Figure 1 - 2 shows the area of coffee plantations along the mountain, more than 90.000 hectares and between 600-1600 m.a.s.l and is divided into 52,000 producers and 192 cooperatives, with 99 coffee mills and 256 micro mills according to the last registries of 2021 from ICAFE. The Region of Tarrazú represents 10% of the Costa Rican coffee producers, and it is recognized for high-altitude coffee production (ICAFE, 2011a).

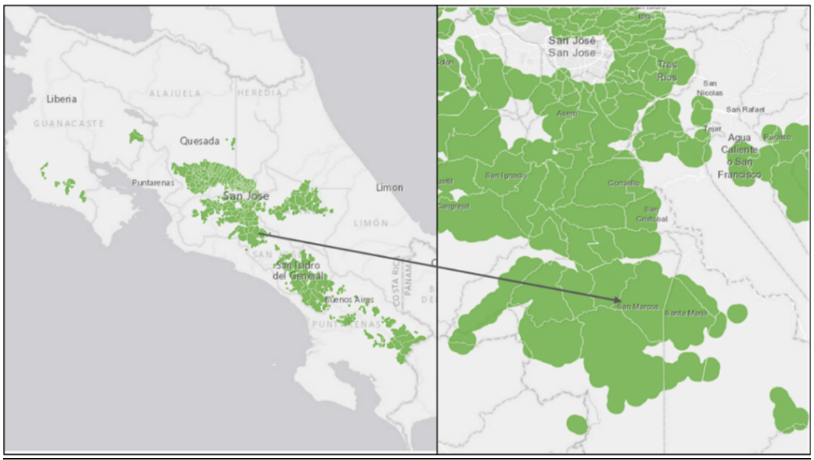

Figure 1 - 2: Regions of Coffee Production in Costa Rica and the zoom up in Tarrazú Region. Source: SIGICAFE.

The harvesters, during each season, are just collecting the red coffee beans in each coffee tree, letting the green coffee berries until they turn to be collected weeks after (Bastian et al., 2021). The study was performed in the country's biggest cooperative (coffee mill) called CoopeTarrazú R.L. Coopetarrazú is a cooperative dedicated to producing and marketing coffee, committed to regenerative agriculture and environmental protection, and sustainable production. According to the mill personnel, the cooperative involves 5000 coffee producers, obtaining around 50.000 t / yr of coffee berries and 37.000 t / year of coffee by-products as residue. When the peels are removed, they are composted to produce fertilizer, and the beans are scrubbed to remove the mucilaginous inner coating and separate the pulp from the coffee. The process is called a washed process, where the beans are sorted by weight and size, passing through large rotating drums filled with water (Chala et al., 2018).

The coffee pulp is transported by truck from the receiving yard to the different composting areas. The piles are formed with a mini wheel loader with approximately the following dimensions: 60 m x 2.6 m x 1.2 m, as shown in figure 1 - 3. Five volume percent (vol%) of husk is added to all piles. A Backhus turner is used for the mechanical turning of the compost. Turning is done daily for 6 - 8 weeks. At the end of the 6-8 weeks, one-third of the same producers collect the treated coffee by-products to spread them on the coffee fields (approximately 5,000 producers). The material is piled up again to optimize space when this material loses the minimum volume. Each fanega delivered has to remove a percentage of coffee by-products since the treatment cannot wait more than one year. For example, 40 fanegas (typical Costa Rican coffee measurement in which one fanega equals 105.2 kg of pulp (SEPSA, 2017)) correspond to 1 m^3 of compost. No treated coffee by-products are transported, but rather, some small cars go to collect the material once it is 6 - 8 weeks old, directly to the area destined to distribute the final product.

Figure 1 - 3: Composting pile at the coffee mill in Costa Rica.

1.3. Coffee by-products

Figure 1 - 4 represents the parts of the coffee cherry and the appearance of the main by-product as a fruit. Coffee pulp (CP) is the first by-product and represents, on average, 43% of the weight of the coffee fruit on a fresh weight basis. However, in some cases reaches up to 50%, or approximately 28% (26 - 30%) on a dry weight basis (DW) (Esquivel & Jiménez, 2012, Elías, 1979).). This implies that for nearly every 2 tons of coffee produced, 1 ton of CP is obtained. The mucilage is about 5% (5 - 14% DW) of the fruit, and the coffee husk is 12% (10 - 12% DW). The thin coffee skin of the bean is removed after bean milling (before roasting (2% DW))(P. S. Murthy & Madhava Naidu, 2012). CP is rich in carbohydrates, proteins, and potassium and contains tannins, polyphenols, and caffeine (Chong & Dumas, 2012a). The organic components present in CP (dry weight) include tannins 1.80–8.56%, total pectic substances 6.5%, reducing sugars 12.4%, non-reducing sugars 2.0%, caffeine 1.3%,

chlorogenic acid 2.6%, and total caffeic acid 1.6% (Ameca et al., 2018; Selvankumar et al., 2017).

The coffee husk (CH) is obtained by a dry method where the grains are dried in the sun or mechanically. The coffee beans are constantly stirred and dried with hot air in a specially designed perforated cylinder drum (P. S. Murthy & Madhava Naidu, 2012). As a result, CH comprehends CP and coffee parchment in a ratio of 1 to 2.5 (coffee cherry = 55% coffee bean, 28% pulp, 12% parchment, and 5% pectin (Guthapfel et al., 2016). On the other hand, the silver skin (SS) is a coffee by-product from the roasting containing a high concentration of phenolic compounds (P. S. Murthy & Madhava Naidu, 2012).

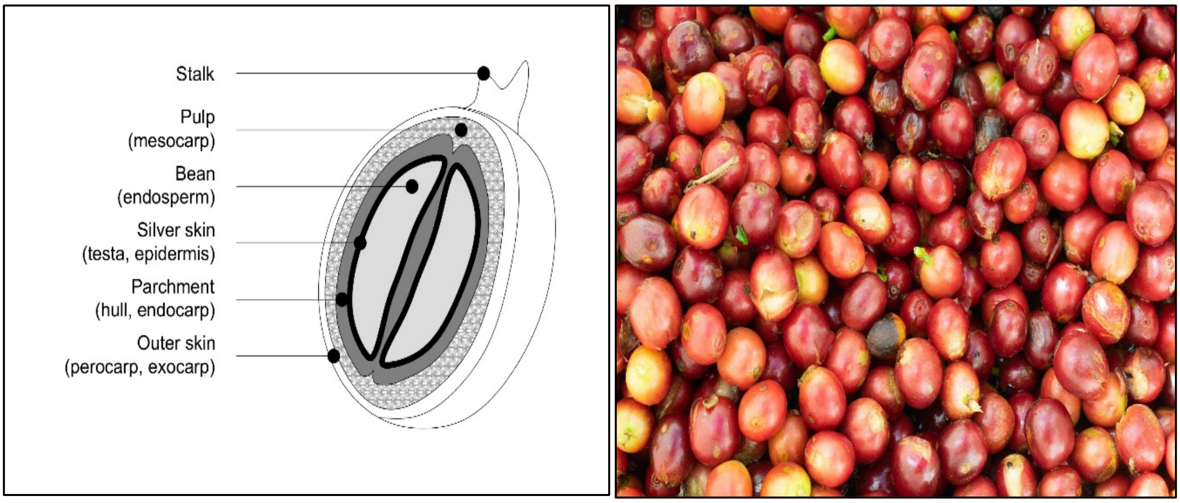

Figure 1 - 4: Coffee cherry in a longitudinal cross-section cutout and fruit.

1.4. Coffee Plantations

Coffee is one of the most developed crops in Costa Rica. Coffee plantations can be found in the main basins used for hydroelectricity generation, which are impacted by soil erosion. There are two main seasons: a dry season from December to April with sparse low rainfall and a rainy season from May to November with heavy rainfall (2.612 mm - 3.992 mm per year). The Ministry of Agricultural Development in Los Santos indicates that there are 125 hectares of coffee plantations in the province (33% - 35% of production), where four varieties of coffee are found. In the Los Santos and Valle del General region, ultisols soils predominate. Due to the physical and chemical limitations of ultisols soils for intensive coffee production, special attention is required to using calcareous and organic amendments, which minimize problems related to acidity and low organic matter content (Chinchilla et al., 2011). Farmers only use small machinery to apply treatments, fertilizers, and weed control. Costa Rica has not adopted a hyper-intensive method. As a result, the expansion of this input has been more restricted (Agergaard et al., 2009). Furthermore, the management and application of suitable fertilizers depend on knowing each soil's chemical, physical, and biological characteristics (Haby et al., 2011). In Costa Rica, the SNF added in coffee plantations suggested by ICAFE in kg x ha^{-1} x yr^{-1} is 287 of N, 20 of P, and 150 of K (The World Bank Group, 2013).

Coffee fertilization is one of the most important practices in coffee cultivation. Plants only absorb the nutrients they require; the remainder, or excess, is simply lost due to volatilization and washing. On the other hand, excessive fertilizer application causes an ecological imbalance in the soil, which affects soil properties (Coopetarrazu R.L., 2020; Kathpalia & Bhatla, 2018). These properties include pH, electrical conductivity, and the balance of ions like calcium, magnesium, and sodium. The plant cannot absorb nutrients when the relationship between the contents of Calcium (Ca), Magnesium (Mg), Potassium (K), and Sodium (Na) in the soil is unbalanced (Kathpalia & Bhatla, 2018). As a result, nutritional deficiencies will develop even in the presence of ions in the soil.

The uncontrolled use of chemical fertilizers, combined with insufficient mechanized tillage practices, is to blame for the soil's loss of productive capacity. When soil is subjected to poor management practices, it experiences negative changes in its physical properties. In most cases, it also loses the organic layer that keeps it productive (Coopetarrazu R.L., 2020). As the organic layer degrades, the physical properties of the soil change. For example, porosity, infiltration, and moisture retention capacity all decrease in this case, while resistance to root penetration increases (Hue & Silva, 2000; Kathpalia & Bhatla, 2018; Rosolem et al., 2017a). Compacted soils have made drainage difficult. In other words, water does not freely circulate within them. This causes salts to accumulate, resulting in the salinization phenomenon. The chemical characteristics of the soil, including pH and the balance of all nutrients, change when there is not enough organic matter present. Plants cannot absorb soil nutrients if they are not balanced, regardless of the amount of ions present (Dhaliwal et al., 2019; Rosolem et al., 2017b). As a result, only 50% of the nitrogen, 70% of the phosphorus, and 40% of the potassium added to a crop as chemical fertilizer are absorbed by the plants. In the case of nitrogen, 50% is lost through volatilization as NH_3 and N_2O. It is also lost to groundwater as NO_3 through leaching (washing). P is immobilized in electrically charged soil mineral particles such as clays and allophanes to 40 - 70%. Alternatively, it precipitates by forming insoluble compounds such as calcium, iron, and aluminum phosphates (Bhusal & Thakur, 2022; Coopetarrazu R.L., 2020). Plants cannot use these PO_4^{3-} because they are insoluble unless the soil contains significant populations of phosphorus-solubilizing microorganisms. These organisms can only be found in large numbers in healthy, balanced soils (Johan et al., 2021). In addition, potassium is a highly soluble element, and much of the potassium in fertilizers is lost through washing and leaching. As a result, when applying chemical fertilizers, it is critical to consider management strategies that allow attenuating some of these losses while maximizing plant uptake. As a result, cp fertilization becomes more efficient and cost-effective (Barrow, 2017; Hue & Silva, 2000).

The Region (figure 1 - 5) has the advantage of having coffee pulp as a secondary product of the coffee harvest (CEDAO, 2017). This is because t concentrations of P, Ca, K, and Zinc (Zn) is in greater quantity in the pulp than in the coffee bean itself; It also contains Mg, S, Iron (Fe), and Boron (B) which are released gradually (Elías, 1979).

Figure 1 - 5: Coffee plantations in Tarrazú Region, Costa Rica.

In coffee cultivation, genetic variation is reduced; 98.5% of the genetic resource is homogeneous. Low genetic variation is a severe problem since the effect of pests and diseases can be devastating (World Coffee Research, 2018). For applications of compost based on the coffee pulp, it is recommended by ICAFE at a dose of 1 kg/plant. This compost complements chemical fertilization (ICAFE, 2011b).

1.5. Composting

Aerobic composting is a process that depends on the amount of air supplied to the microorganisms to break down the available carbon resources to produce carbon dioxide and water. Therefore, composting processes can be considered a complex network of parameters that influence, interact and counteract each other physically and chemically (VDI 3475 part 2, 2005). The heat flux is then used as an indicator of composting success. Aeration can help control it (heat removal by ventilation or turning). The four interacting factors during the composting process are metabolic heat generation, temperature, ventilation, and humidity (Azim et al., 2018). Successive microbial populations carry out the decomposition of organic matter. Mesophilic microorganisms (between 20 and 40 °C) and species that can withstand temperatures up to 50 °C occur first. All thermophilic bacteria are active at various phases of the composting process (up to 70 °C) (Papale et al., 2021). The first composting stage is characterized by the self-heating of organic matter and its intense decomposition. In this stage, thermophilic microorganisms predominate, working at an optimum temperature of 55 °C (Bidlingmaier, 2003; Clarence G. Golueke, 1973).

Externally, the composting process is heavily influenced by environmental conditions, the method used, and raw materials that may vary during each process. However, they must be constantly monitored to remain within an optimal range (Ajmal et al., 2020).

In addition, the initial composting phase releases organic acids, increasing the pH, and the final compost product should have a neutral to slightly basic pH (Simandi et al., 2005). The second phase of composting occurs under mesophilic temperatures, called the maturation phase. Here, macromolecules are degraded by specialized microorganisms (VDI 3475 part 2, 2005). Finally, an adequate carbon to nitrogen ratio (C: N ratio) is desired, as this ratio significantly influences microbial activity (Shafawati & Siddiquee, 2013). Organic material can be composted in a wide pH range (3 – 11), and the ideal range is between 5.5 and 8 (Sundberg et al., 2004, 2013).

Values near neutrality are ideal for the development of microorganisms. On the other hand, Fungire more resistant to distant neutral pH than bacteria (Taiwo & Oso, 2004). Because of the organic acids released during the decomposition of simple organic substrates and the volatilization of the initial ammonia, the pH may decrease during the first composting stage. Conversely, the decomposition of easily degradable organic materials and mineralization increases pH. Temperature also influences pH evolution, favoring ammonia volatilization (Sundberg et al., 2004, 2013).

Such microorganisms can regulate minor environmental disturbances; however, the following criteria must be considered: At elevated temperatures (above 75 °C), a large part of the microorganisms are inactive due to the previous conversion of high organic content (Haug, 1993). As a result, highly volatile metabolites are concentrated in the wet phase of the material (Said-Pullicino et al., 2007). These are released by the high evaporation rate that co-occurs. On the other hand, an increase in the temperature of the intensive degradation phase is desired because, at elevated temperatures of 55 °C to 60 °C, pathogens are eliminated, and complete sanitization is achieved (de Guardia et al., 2010; Jenkins, 2011).

Several parameters must be considered during composting in terms of efficiency. Some are bulk density, porosity, particle size, nutrient content, C/N ratio, temperature, pH, moisture, and oxygen supply to avoid undesirable odors, dust, and the obtention of a high-quality agricultural product (Bernal et al., 2009). In addition, it is essential to take into consideration the maturity and stability of the compost before applying it to land to avoid severe effects on the plant growth in case there is a presence of pathogenic microorganisms and nutrients that can harm the biota and the stability of the soil (Sudharsan Varma & Kalamdhad, 2014).

The carbon to nitrogen (C/N) ratio is an important factor influencing the composting process and the end-product properties (Kumar et al., 2010a). Adequate C/N ratios in composting have been reported to range between 25 and 30 (Jiang et al., 2011; Kumar et al., 2010a), and the ideal C/N ratio is around 30 to ensure carbon energy intake while allowing microorganisms to grow quickly (Clarence G. Golueke, 1973; Haug, 1993).

Moisture is a microorganism-related parameter, and a content of 45 to 50 percent is ideal for composting. When moisture levels are less than 30%, bacterial activity is limited, and moisture levels above 65% reduce the porosity of the compost, resulting in anaerobic growth and unpleasant odor emission(Liang et al., 2003; Richard et al., 2002).

Compost bulk density measures the mass of material contained within a given volume (Haug, 1993). It influences mechanical properties such as strength, porosity, and ease of compaction. Typical dry bulk densities range from 100 kg $(m^3)^{-1}$ to 400 kg $(m^3)^{-1}$, whereas wet bulk densities range from 500 kg $(m^3)^{-1}$ to 900 kg $(m^3)^{-1}$ (Agnew & Leonard, 2003a). Higher bulk density values indicate an increase in mass while decreasing porosity and air volume. On the contrary, extremely low wet bulk density can indicate excessive substrate aeration and, as a result, a decrease in the available water fraction (Agnew & Leonard, 2003a; Ajmal et al., 2020). The compost's stability and maturity are critical for its use as an amendment and nutrient source for plants (Nakasaki & Marui, 2011). For compost quality, there are two different methods in use: The first method is predicated on converting an initial unstable organic matter into a stable organic matter at the completion of composting. As a result, to calculate the stability of the compost, the biodegradability of organic elements and their level of humification is utilized. The second approach considers the effects of compost on plants (Azim et al., 2018). Some researchers found that adding immature compost to soil negatively impacts plant germination, growth, and development. The best indicator of compost maturity in this context is phytotoxicity (Azim, 2018; Haug, 1993; Sánchez-Monedero et al., 2001).

Due to their intense activity, microorganisms in immature composts produce heat during the degradation of the simplest and most accessible compounds. Thus, the temperature rise after moistening can be used to determine the degree of decomposition of organic material in a compost (self-heating test). Several studies have demonstrated the utility of this test in determining the maturity of composts (W. F. Brinton et al., 1992).

1.6. International literature review

1.6.1. GHG Emissions in the coffee sector

The unsustainable growth of agriculture for more than 100 years, intensive agriculture and tillage have reduced soil carbon by 30 to 50%, is the primary water and soil contamination source by nitrates, phosphates, and pesticides, severely influencing climate change (FAO, 2021). Agriculture is responsible for almost 11% of greenhouse gas emissions, particularly CO_2 and N_2O emissions (Feliciano et al., 2022). Deforestation affects sensitive ecosystems that protect atmospheric dynamics, water, and wildlife (UNEP, 2007). Agriculture, forestry, and land use changes from natural forest to agricultural contribute one-third of the radiative forcing caused by these trace gas emissions, including a sizable portion of the N_20 (Dervash et al., 2022), Smith et al., 1997,). The increased atmospheric N_2O concentration is primarily attributable to the expanding use of N fertilizer in agriculture. Crops, in particular, use significant quantities of chemical pesticides and synthetic fertilizers that contribute to the change in the regular cycles of nature (Krebs & Bach, 2018). Coffee monocultures managed without sustainability measures discharge emissions and compounds. These compounds contaminate the environment and rivers, mainly provoking eutrophication and global warming (Varcho, 2008). Coffee production makes up about 7.5 percent of all permanent crops worldwide and requires high quantities of SNF (150-350 kg N x ha $^{-1}$ x y^{-1}). Therefore, it may have a significant impact on future increases in atmospheric N_2O (Hergoualc'h et al., 2008).

The soil in Costa Rica is naturally acidic (4.5 – 5.0) (ICAFE, 2011a). High soil acidity can impair root development by disrupting essential elements such as K, magnesium, calcium, and P and releasing others of a toxic nature, such as aluminum (ICAFE, 2011a). Direct emissions result from applying animal manure and fertilizers to agricultural soils, manure production in fields, crop residues left on the field, biological nitrogen fixation by crops, and organic crop soils (histosols) (van der Hoek et al., 2007). The direct emission can be obtained through formulas that use the nitrogen nutrient consumptions of N fertilizers and emission factors determined by the Food and Agriculture Organization (FAO) through global data of coffee producers of the countries. On the other hand, indirect emissions result from subsequent leaching of nitrates of agricultural origin from soils to groundwater and surface water. In addition, the deposition of ammonia volatilized due to agricultural activities contributes to indirect nitrogen oxide emissions (van der Hoek et al., 2007). The emission factor for coffee plantations in Costa Rica has been established by the National Meteorological Institute (IMN). A study conducted in the late 1990s shows that the N_2O emission factor is approximately three times higher in coffee plantations without total sun exposure than in the under-regulated shade, as table 1 - 1 shows. However, these studies were conducted with a single dose of nitrogen, so it is a model that applies only to coffee plantations with a similar fertilization level (ICAFE, 2011).

Table 1 - 1: Emission factors estimated by the Costa Rican National Meteorological Institute (IMN) for coffee plants (IMN, 2020).

Crop	**Area planted m^2**	**Emission Factor kg N_2O x ha^{-1} x y^{-1}**	**N_2O Emissions Gg x y^{-1}**
Shaded coffee	60.953	7.78	0.474
Coffee without shade	31.700	2.92	0.093

The main emissions hotspots in Costa Rica come from fertilizer production and direct and indirect soil N_2O emissions per year from organic fertilizers (such as chicken manure and coffee pulp) (Noponen et al., 2012). In other words, it can be said that the main contributors to GHG are organic and inorganic nitrogen inputs (Kilian et al., 2013). The emissions from coffee by-products are mainly produced during its use in agriculture with inadequate or excessive use of fertilizers and aerobic treatments (composting), as table 1-2 shows.

Table 1 - 2: Emissions of GHG from coffee by-products (Amlinger et al., 2008; Groot, 2012; Himanen & Hänninen, 2011; Jamaludin & Mahmood, 2008).

Process	**Stages of emissions**	**By-products used for the process**	**Emissions**	**Sources of emissions**	**Advantages of the process**	**Comments on Emissions**
Composting Aerobic (open system &)	Mesophilic (20ºC – 40ºC) Thermophilic (50ºC - 70ºC) Maturation <45ºC	CP, CH, SC, SS	CH_4 CH_4, NH_3 N_2O, Leaching	Mixture & environmental conditions. Agricultural activities, fertilizers, waste management, mixture composting, energy use, and biomass burning.	Carbonaceous materials, reduction of input material, energy source & fertilizers with low cost.	Emission depends on the kind of mixture. Oxygen availability, ammonium, and ammonia concentrations are key factors for N_2O formation. C/N ratio < 25 will help to minimize NH_3 and N_2O emissions

CP: Coffee Pulp, CH: Coffee Husk, SC: Spent Coffee (the residue obtained during the brewing process), SS: Silver Skin.

1.6.2. Composting Coffee by-products

In recent years, adaptation to climate change has gained global importance. However, despite international efforts to mitigate GHGs under the Kyoto Protocol, the effects of global warming are known to occur and will increase in the coming years (Gustavsson et al., 2000; Haddow & Pike, 2017). For this reason, Costa Rica has decided to act immediately, unilaterally declaring its goal of avoiding net carbon emissions.

Furthermore, Costa Rica is preparing an integrated climate change strategy to achieve carbon neutrality so that these complex goals can be replicated in other countries. Creating a National Climate Change Strategy will generate a tool that will facilitate decision-making, define priorities, and determine a monitoring mechanism that will legitimize the goal of carbon neutrality by 2050 (UN, 2021).

Composting is one alternative to managing coffee by-products. Composting allows for a second use of the material as a soil amendment, reducing environmental impacts and reserving a significant amount of water, helping to prevent or reduce erosion, runoff, the growth of vegetation, and the emission of greenhouse gases (Girmay et al., 2016). Worldwide, coffee by-products are of great interest, especially converting the products into usable end products. To tackle this conversion is essential to understand the crop production to give a widespread use and the most suitable endorsement by the end uses of the by-products (Esquivel & Jiménez, 2012; M, 2021; P. S. Murthy & Madhava Naidu, 2012).

Table 1 - 3 summarizes the composting application of coffee by-products internationally. The results reveal that almost every country mentioned in the table of coffee producers uses the composting process as the easiest method to treat the coffee by-products. This is primarily through windrows because of its feasibility application, low investment, and not necessarily high technology or specialists during most of the processing time. The investment required and the available technology are limitations to applying industrial processes for coffee by-products in undeveloped countries. CP is the most significant coffee waste product, but only a few countries are testing new mixtures to improve the final product as compost.

Another significant potential source of GHG emissions is the treatment (disposal) of residues. That consists mainly of the skin of the coffee, pulp, and husk). Furthermore, the wastewater possesses high organic content, acid, and high oxygen demand in surface waters during coffee processing (Sevenster & Verhagen, 2010).

1.6.3. Costa Rican Legislation

Costa Rica has been wholly engaged in global climate change and, through National Law 8219, ratified the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). UNFCCC recommends implementing a series of actions, such as national programs to improve the quality of water, emission data, activity data, and cost-effective local models that reflect the socio-economic conditions (Campos-Gallo, 2015).

National programs also included actions to mitigate climate change and facilitate adequate adaptation, such as those in the energy, transportation, and industrial sectors, as well as agriculture, forestry, and waste management (OECD, 2020). For example, law Nº. 2762 is a unique model that regulates the relations between producers, processors, exporters, and coffee roasters. The coffee industry in Costa Rica is divided into four sectors, and this law governs each of them to ensure that each sector participates fairly (OECD, 2020; ICAFE, 2017). On the other hand, the National Forestry Finance Fund (FONAFIFO) provides opportunities for farmers to benefit from tree planting and other climate change mitigation. In addition, the Innovation and Agricultural Technology Transfer Institute (INTA) enhances climate-smart agriculture (CSA), having the aim of providing food security and removing/reducing GHGs practices (Valenciano-Salazar et. al, 2022; Costa Rican Government, 2008).

NAMA coffee (Nationally, Appropriate, Mitigation Actions) was defined at United Nations Climate Change Conference (COP16) in 2010 in Mexico as a support project offering mitigation tools and Adaptation, Food Safety, technical, and policy advice. This is to change production and process practices in different sectors, which are the source of 10% of the country's greenhouse gas emissions (Cancun Agreement, 2010) (UNFCCC & NAMA, 2015).

The Costa Rica Solid Waste Plan (PRESOL for its acronym in Spanish) was declared public and national interest by Executive Decree No. 34647-S-MINAE (Ministry of Environment and Energy of Costa Rica). It arose from the need to solve the problem of poor solid waste management and its negative environmental and health impacts in the country. It was also based on the creation of the Multilevel Commission for Integrated Waste Management (IRWM). (Costa Rican Government, 2008).

The needs of the stakeholders involved in the issue, the Action Plan for IRWM 2019-2022 is built based on the agreements reached in the Government Council and directly linked to the Sustainable Development Goals (SDGs), specifically SDG 11, with the Decarbonization Plan (2018-2050) in its axis seven and with the National Development and Public Investment Plan 2019-2022 (Polimeni et al., 2020). Moreover, according to the FAO, Costa Rica possesses a National Climate Change Adaptation Policy (2018 - 2020), prioritizing sustainable production and enhancing adaptation based on ecosystems and water security facing climate change.

Table 1 - 3: Applications of coffee by-products

Methods	Country	Mixtures
Composting		
Vessel-composting	Ethiopia (Chane Abate & Sauerborn, 2002)	10%-50% of CP
	Ethiopia(Kassa et al., 2012; Shemekite et al., 2014)	CP + CD (4:1), CH + fruit / vegetables (2:1), CG (1:1), CP + CH + CD + *Millenia ferruginea* (4:3:2:1)
Windrow composting	Mexico (Sánchez et al., 1999)	CP + FC + Poultry (chicken manure & rice husk) + wood chips (5 : 3 : 2 and 7 : 2 : 1)
	Vietnam (Dzung et al., 2013)	CH + CD (10%) + Lime (2%) + Phosphate (5%) + Urea (1%)
Aerated Static Pile	Puerto Rico (Chong & Dumas, 2012b)	CP + SC + CC
Vermicomposting	El Salvador (N. Wu, 1995)	CP or CH + Manure
	Malaysia (Jamaludin & Mahmood, 2008)	CD (70:30%), SC + Kitchen Waste (35:30:35%)
BSL	Indonesia (Permana & Ramadhani Eka Putra, 2018; Rosmiati et al., 2017)	CP, SC
Others		
SSF (Mushroom strains)	Mexico, Cuba, Brazil (García-Oduardo et al., 2011; Martínez-Carrera et al., 2000; Mateus et al., 2017)	Cacao, Coconut, Cedar wood, Barley, wheat straws, Sugar cane bagasse, corn stubble, and organic materials
Animal Feed	Ivory Coast, Costa Rica (Bouafou et al., 2011; CEDAO, 2017)	CP (dried), SC
Biofuels and Coffee Oil	Morocco (Calzada et al., 1986; Chergaoui Sara, 2017)	SC
Dyes	Uganda (Girotto et al., 2018)	Coffee leaves, SC
Food Industry and flavors	Costa Rica, Spain, United Kingdom (Elba et al., 2017; Moreno et al., 2019; P. Murthy & Naidu, 2012)	SS, CP
Particleboard and Construction	Ethiopia (Bekalo & Reinhardt, 2010)	CH + Wood 50:50, SC + Steel Slag 70 : 30
Sorption of H_2S heavy metals Cu^{+2}, Cd^{+2}, Zn^{+2}	Poland, Brazil (Nowicki et al., 2014; Oliveira et al., 2008)	CP, CH
Waste water decontamination	China, EEUU & Belgium (Anastopoulos et al., 2017; Kyzas, 2012)	CP, CH, SS & SC
Remove Basic dyes	Japan (Hirata et al., 2002)	CP, CH, SS & SC
Pyrolysis	Colo mbia (Conesa et al., 2016)	CH

CP: Coffee Pulp, CH: Coffee Husk, SC: Spent Coffee (the residue obtained during the brewing process), FC: Filter Cake (sugar factory), SS: Silver Skin, CC: Common Compost, CD: Cow Dung, SSF: Solid State Fermentation, Black soldier fly larvae (BSL).

1.7. Objectives of the cumulative dissertation

The primary purpose is to develop an innovative experimental methodology for sustainable management and improved treatment of coffee by-products for soil amendment production. This can be used in crops, including coffee plantations, and, at the same time, to identify the relationship between the form and distribution of N_2O emissions in coffee plantations. These two aspects are the most relevant for GHG emissions in the sector. Therefore, the dissertation aims to provide evidence-based results about emissions reduction and sustainable management of coffee by-products for future use in coffee plantations (Figure 1-6). The findings are published in three peer-reviewed papers and presented in the remainder of the dissertation in a cumulative structure. This means that the three publications are presented in chronological order, corresponding to the date of their publication, and are called publications accordingly Publication I, Publication II, and Publication III. In addition, two of these publications analyze the composting process and feasibility of CH_4 emissions reductions. The third publication comprehends the evaluation of the fertilizers used in coffee plantations and compares the usage of coffee by-products produced during the research. Finally, the results of the three publications are summarized, compared against each other, and discussed in section 6 ("general discussion"). This thesis investigates and answers research questions following the main objectives and their targets.

For years, the coffee industry has been dealing with coffee waste and excessive use of fertilizers due to the high demand for the beverage; therefore, actions to reduce the environmental impact must be addressed (P. S. Murthy & Madhava Naidu, 2012a; Osorio-Arias et al., 2020).

The first publication (San Martin Ruiz et al., 2020), based on the first research question's scope and the basics of the process, focuses on the behavior of the pulp, whether it can be used to make compost, and how much CH_4 emissions are reduced when more materials are added. Field testing in Costa Rica is considered and contrasted with the existing handling and treatment of pulp during composting production in the second part oft he research (San Martin Ruiz et al., 2021). The objective is to generate a finished product in the field process while adhering to the crucial composting criteria and to evaluate the use, conceptualization, and replicability of the composting process during the harvest cycle.

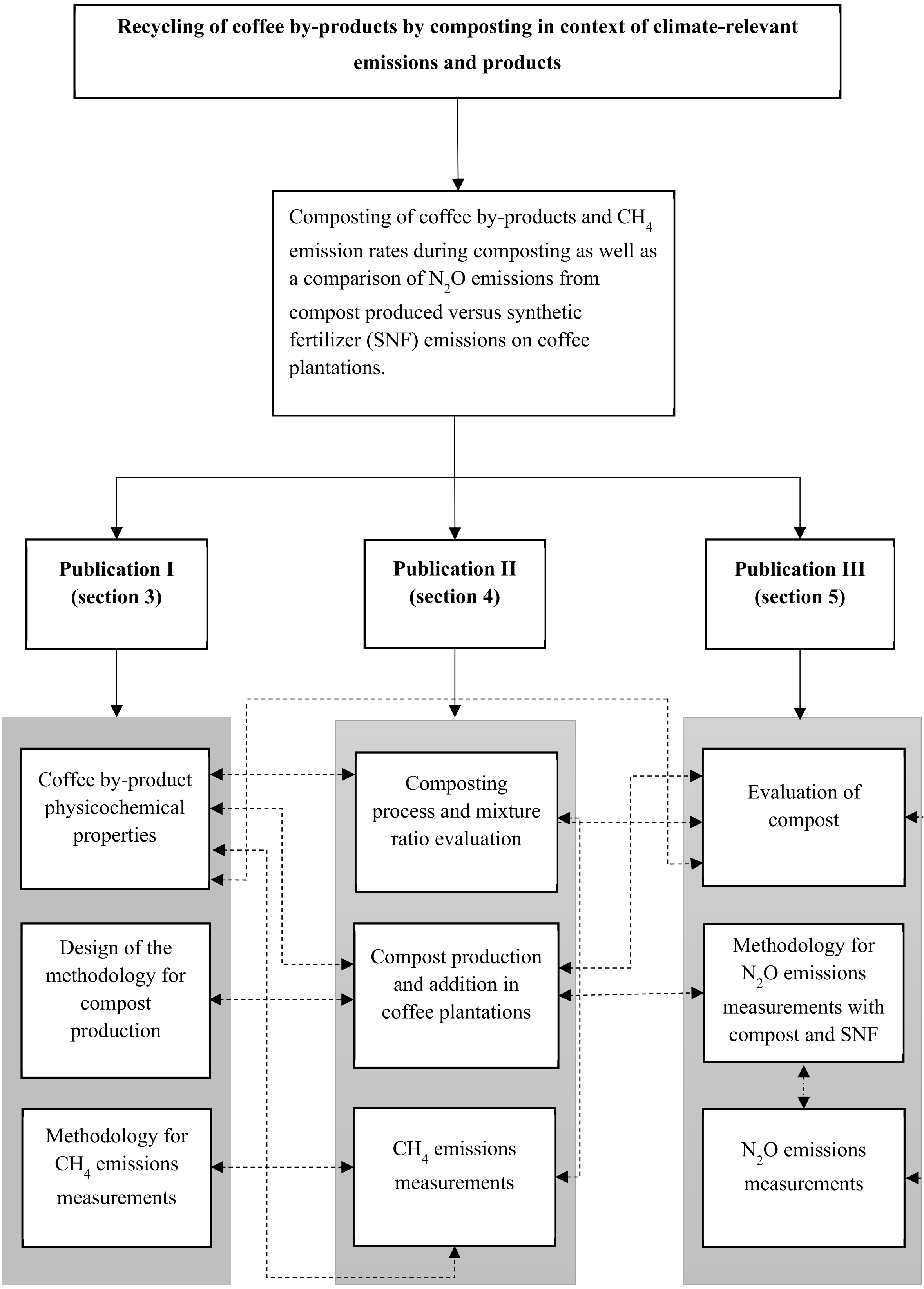

Figure 1- 6: Block diagram highlighting the main research objectives and the relationship between these and the publications reported.

Finally, to close the research loop, the compost produced in the second part, is added to the coffee plants' soil in the research plots to determine how it performs in the coffee plantations once it is added, particularly regarding N_2O emissions.

The third paper (San Martin Ruiz et al., 2021), also compares the different fertilizers (inorganic fertilizers of physical and chemical composition) and the organic amendment created during the field trials in Costa Rica by determining how N_2O emissions behave during fertilization in coffee plants. This was done to compare emission fluxes between the methods used to process coffee (San Martin Ruiz et al., 2021), and determine emission fluxes when various fertilizers are utilized.

The dissertation, therefore, focuses on a central research question:

Does recycling coffee by-products an alternative to farm practices on coffee plantations to reduce climate-relevant emissions?

(San Martin Ruiz et al., 2020), investigates the methodology of using coffee by-products for composting and the methane emissions fluxes when different materials are added to the coffee by-products. Therefore, the following questions were raised during the investigation:

1.1) What are the constituents and physical-chemistry properties of the coffee by-products and inputs materials?
1.2) What is the behavior of the aerobic composting process when green waste is added?
1.3) Which factors affect the composting process?
1.4) How to quantify and obtain emission rates with the methodology proposed?
1.5) Is it possible to obtain a methane reduction when green waste is added to a composting plant in Germany compared to the control in Costa Rica?

(San Martin Ruiz et al., 2021), evaluates an experimental methodology for coffee by-products as nutrient-rich compost in the study area. Moreover, the aim is to quantify methane emissions rate and the obtention of an emission factor and compare different mixtures with the status quo. The outcome addressed the following research questions:

2.1) What difference does composting parameters and biological activity in the different percentages of mixtures with coffee by-products and green waste make?

2.2) How are the methane emissions in the study field compare weekly with the control of the coffee mill?

2.3) Which treatment obtained the most suitable nutrient content and finished compost for the coffee plantations?

2.4) Is it possible to reduce emissions depending on the percentage of the mixture of green waste added?

2.5) Are the emission factors directly linked with the coffee pulp management in composting?

(San Martin Ruiz et al., 2021), explores a measurement strategy for nitrous oxide emissions and its influence when different fertilizers and soil amendments are added. Moreover, an investigation of emissions following the practices in the coffee plantation was addressed when two types of coffee varieties fertilized were added. The results aimed to respond to the following research questions:

3.1) Is it possible to develop a methodology for quantifying nitrous oxide emissions on coffee plantations?

3.2) What is the relationship between the type of fertilizer added to the soil and the amount of nitrous oxide emitted?

3.3) What difference makes the variety of coffee analyzed?

3.4) Are the fertilization period, climate, and nitrous oxide emissions closely related?

3.5) What is the difference in nitrous oxide emissions when fertilization trials are made, and soil amendment of coffee by-products are compared?

The dissertation also aims to provide a broad vision of greenhouse gas behavior and emission rate in the coffee sector during fertilizers and the management of coffee by-products for compost production.

Structure

The cumulative dissertation is divided into six sections:

- **General introduction (section 1)**

- **Materials and Methods (section 2)**

- **Publication I (section 3)**

San Martin Ruiz, M., Reiser, M. & Kranert, M. Enhanced composting as a way to a climate-friendly management of coffee by-products. *Environ Sci Pollut Res* 27, 24312–24319 (2020). https://link.springer.com/article/10.1007/s11356-020-08742-z . License: CC BY.

- **Publication II (section 4)**

San Martin Ruiz, M.; Reiser, M.; Kranert, M. Composting and Methane Emissions of Coffee By-Products. *Atmosphere* 2021, *12*, 1153. https://doi.org/10.3390/atmos12091153. License: CC BY 4.0.

- **Publication III (section 5)**

San Martin Ruiz, M.; Reiser, M.; Kranert, M. Nitrous Oxide Emission Fluxes in Coffee Plantations during Fertilization: A Case Study in Costa Rica. Atmosphere 2021, 12, 1656. https://doi.org/10.3390/atmos12121656. License: CC BY 4.0.

- **General discussion (section 6)**

- **Synthesis, conclusions, and outlook (section 7)**

2. Materials and Methods

The research was divided into two main groups: the composting process and sustainable management of coffee by-products and methane measurements (San Martin Ruiz et al., 2020, 2021). The second group comprehends the behavior of the fertilizers, types of SNF, and soil amendment made during the first group of this research to estimate N_2O emissions on coffee plantations when fertilizer and soil amendment is applied (San Martin Ruiz et al., 2021).

2.1. Composting

The research was conducted in four phases, represented in figure 2 - 1.

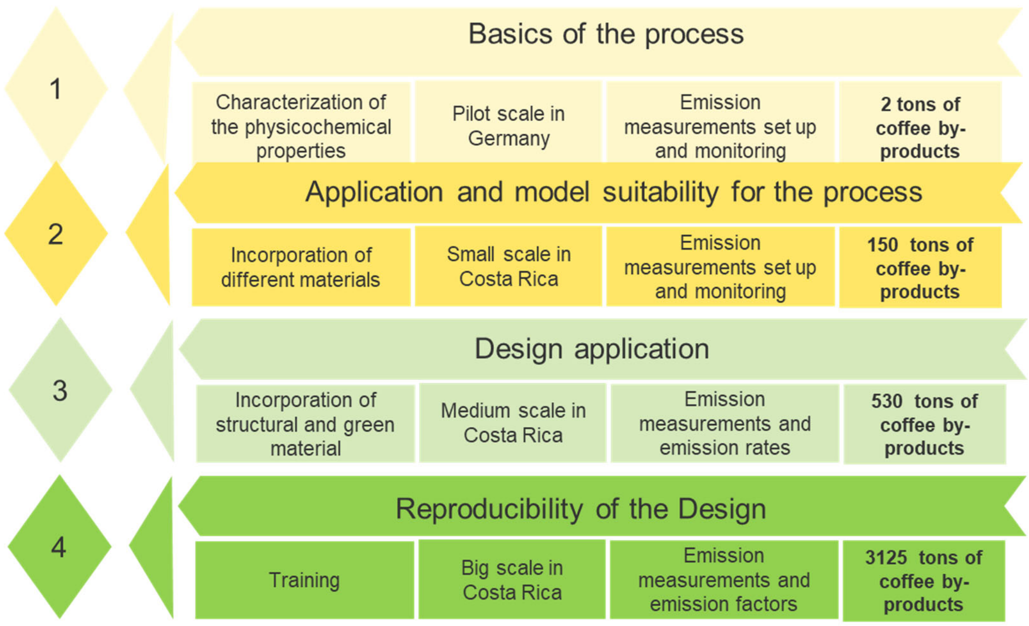

Figure 2 - 1: Composting project-concept.

2.1.1. Basics of the process

During the research phase, four different composting processes were developed to test the different mixtures of materials and how they reacted throughout the composting process. Each had a different or additional component. This step was critical in determining whether it was feasible to convert coffee pulp into compost at various percentages of green waste mixture

(GW), such as grass clippings and weeds, and structural material, including tree pruning from the surroundings, including coffee plants. The processes are divided into two different facilities. The tests were conducted in 335 and 140-liter tumblers (treatment I, II, III). The first one is located within the Institute for Sanitary Engineering, Water Quality, and Waste Management (ISWA) facilities at the University of Stuttgart. The second part (treatment IV) was located on the premises of a composting plant in Stuttgart (composting plant facility Abfallwirtschaftbetrieb Landkreis Böblingen). During this phase, as figure 2-2 shows, the experiments were carried out on the rotating drums between 6 to 8 weeks as:

1. Treatment I: 50% CP - 50% CH.
2. Treatment II: 50% CP - 40% CH - 10% GW.
3. Treatment III: 50% CP - 50% GW.
4. Treatment IV in a compost pile: 50% CP - 50% GW.

Figure 2- 2: Tumbler trials using coffee by-products. 1: treatment I, 2: treatment II, 3: treatment III, 4: treatment IV.

2.1.2. Application and model suitability for the process.

During this phase, the composting process in Costa Rica was designed as a small-scale design to evaluate all the materials available near the mill to understand the behavior of the coffee pulp when it was mixed at different ratios with the materials. Figure 2 - 3 shows the treatments, having a total of 10 different mixtures, where at least 50% of coffee pulp was used as a primary input for the study and is as follows:

- Treatment 1: 60% CP - 40% GW.
- Treatment 2: 50% CP - 30% GW - 20% processed CP.
- Treatment 3: TC : 99% CP - 1% CH on edges.
- Treatment 4: 85% CP - 15% CH.
- Treatment 5: 33.3% CP - 33.3% sawdust - 33.3% processed CP
- Treatment 6: Treatment 1 under the roof.
- Treatment 7: Treatment 2 under the roof.
- Treatment 8: 40% CP - 35% GW - 20% processed CP - 5% ashes.
- Treatment 9: Treatment 5 under the roof.
- Treatment 10: 50% CP - 20% GW - 10% sawdust - 20% processed CP.

Figure 2 - 3: First trials in Costa Rica using coffee by-products.

2.1.3. Design application

Throughout the study, logistics were developed with the mill personnel to analyze the alternatives proposed. Before the harvest, a plan was developed to collect materials to make the mixtures. After the mixture with different materials was tested in the second phase, the treatments (percentage based on volume) were decided based on the feasibility of the cooperative in collecting the input materials. In this phase, the main objective was the feasible mixture, mixing structural material and grass, and obtaining the best mixture ratio with coffee pulp. With that, the emissions can be evaluated, monitoring the composting process and obtaining the differences in performance and emissions with each mixture proposed. Figure 2-4 shows a representation of the piles and the mixtures (by duplicate) used in each treatment area as follows:

- Treatment 1: TC (control 100% CP).
- Treatment 2: 80% CP - 20% GW.
- Treatment 3: 75% CP - 25 % GW.
- Treatment 4: 70% CP - 30 % GW.
- Treatment 5: 60% CP - 40% GW.
- Treatment 6: 50% CP - 50% GW.

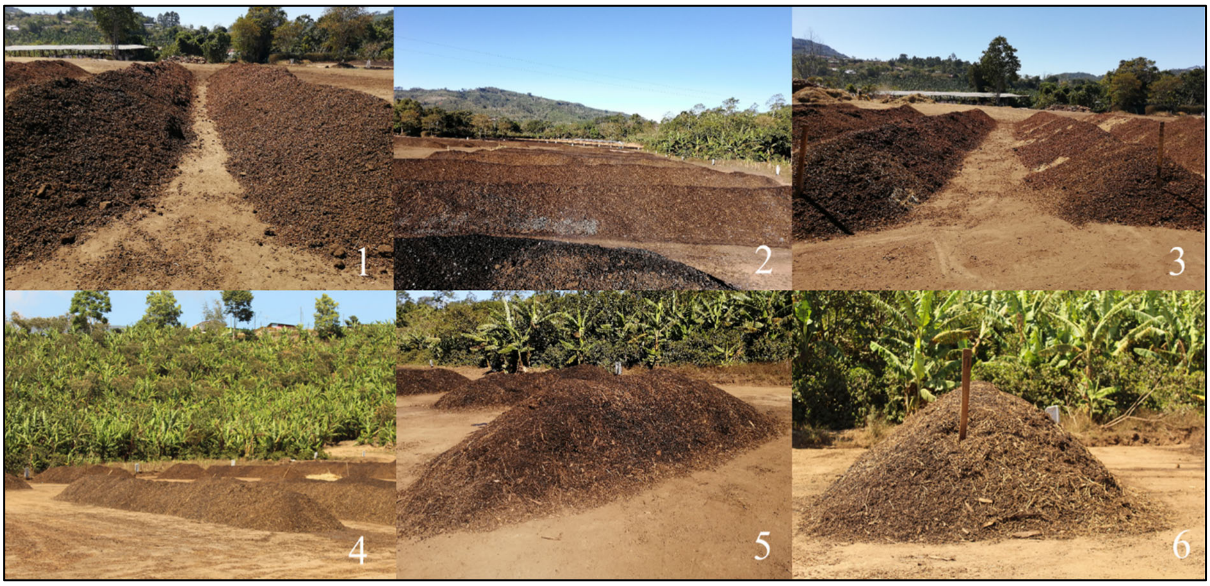

Figure 2 - 4: A medium-scale pilot project is designed and implemented in Costa Rica after a three-week composting process. Image 1 shows the control of 100% coffee pulp. Images 2 through 6 correspond to treatments using mixtures from 20, 25, 30, 40, and 50% green waste, respectively. The pictures show the size and spacing between each pile and how the material appeared in various combinations of green waste.

2.1.4 Reproducibility of the design

The final phase consisted of replicates from the third phase. The selection of the mixtures was made according to the final decision of the mill. Also, it is a realistic approach for the collection of the material. This was made to monitor the behavior of the emissions and corroborate the methodology proposed, ensuring that the material can follow a pattern during future harvests, where the mill can implement the methodology. Figure 2 - 5 represents the selected mixtures, where just two mixtures were monitored (by triplicates) and compared to the control and are as follows.

- Treatment 1: 70% CP - 30 % GW.
- Treatment 2: 80% CP- 20% GW.
- Treatment 3: TC.

The parameters controlled during the entire process followed the Bundesgütegemeinschaft Kompost e.V. (BGK) recommendations, such as temperature, pH, apparent density, ignition loss, Dewar test (self-heating), water content, and C/N ratio (BGK, 2017). The first measurements were made using a sampling bag through a chamber method to test and make the gas collection setup. The bag was made of Nalophan, and the gas samples were analyzed using Fourier-transform infrared spectroscopy (FTIR) from Gasmet Technologies GmbH, Karlsruhe, Germany. For the experiments made in Costa Rica, a gas detector device (Multitec 540 from Sewerin©) was used to quantify the methane concentrations in the composting piles.

Figure 2 - 5: Reproducibility of the design on a big scale in Costa Rica using coffee by-products. The left section represents the treatment with a 30% green waste mixture, whereas the right section shows an aerial photo of all the treatments with mixtures of 30% green waste(1), 20% Green Waste (2), and 100% Coffee Pulp (TC) (3).

2.2. Coffee plantations

The methodology and details used during this study are explained in (San Martin Ruiz et al., 2021), where the results, methodology, and discussions carried out for this section are shown. Figure 2 - 6 shows the project concept for measuring N_2O emissions in coffee plantations.

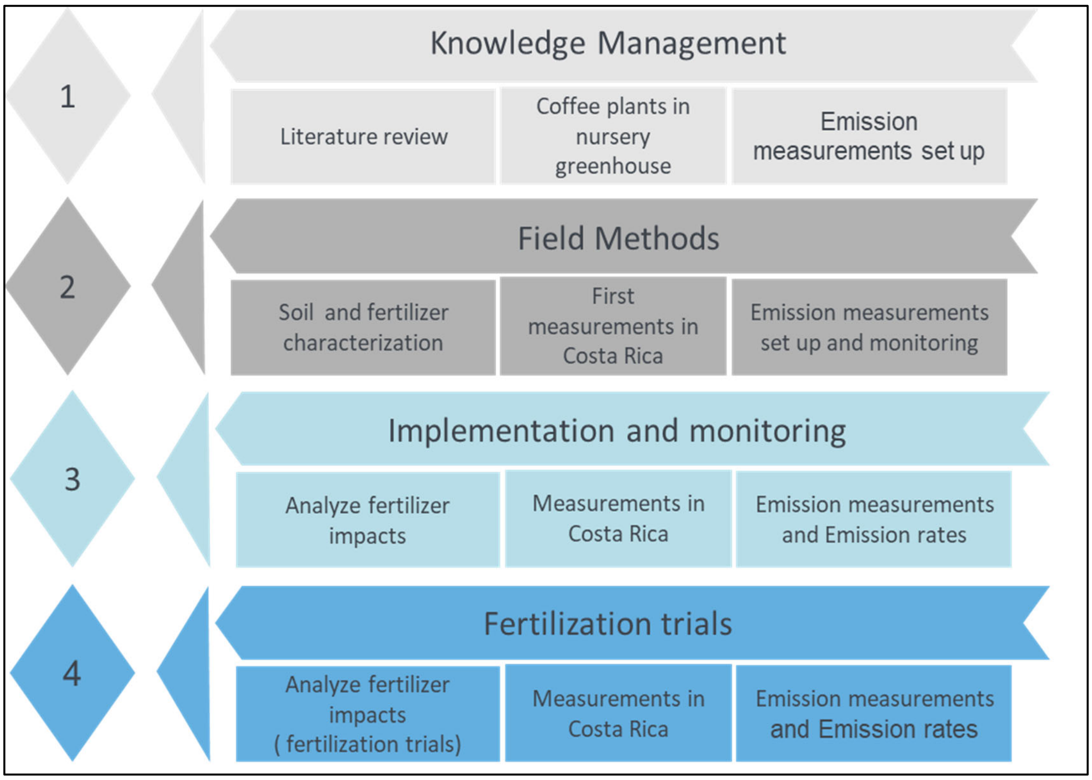

Figure 2 - 6: Coffee plantations project-concept.

2.2.1. Knowledge Management

In the first phase, a literature review, understanding, and collection of fertilizer used in coffee plantations in the study area were made. On the other hand, setting up a methodology for N_2O measurements was essential. Therefore, the pilot design was made in a nursery greenhouse in a zoological–botanical garden Wilhelma in Stuttgart, Germany (figure 2 - 7), to prepare the equipment for measuring the emissions in the coffee plantations in Costa Rica. As a basis for developing a methodology for measuring N_2O in the coffee plantations in the cooperative's plots, some test measurements were carried out, focusing on the direct emission of coffee plants in the nursery and greenhouse soils at the Wilhelma Zoo in Stuttgart. The main reason is that the procedure is carried out on a point scale and not in a massive monoculture. Among the botanical collection was the area of coffee plants, with some species such as Arabica growing in greenhouses planted inside the facilities. Most of the coffee plant species at Wilhelma are

Arabica species imported. Others are donated as seeds or plants from individuals or professionals dedicated to agricultural activity. The nursery maintains adequate temperature, initial fertilization, soil pH, and UV irradiation under a metallic/glass infrastructure to obtain coffee plants with similar conditions as in tropical areas. The chamber method was used to collect the gas and analyze using an FTIR.

Figure 2 - 7**:** Setup and first measurements at the greenhouse in the zoological–botanical garden Wilhelma in Stuttgart, Germany.

2.2.2. Field Methods

The plots were selected in the coffee plantations in the mill in 2019. Different scenarios were considered, such as the type of elevation of the plantations, variety of coffee, period of fertilization, and years of the coffee trees. The methodology proposed is to ratify the existence of these emissions in the coffee crops during the harvest season and when fertilizers are added to obtain the first information on the concentration and emission rates in the study area. Catuai and Geisha varieties were taken into account to quantify the punctual N_2O emissions at different months of the year to obtain differences and corroborate the linearity of the N_2O emissions with fertilization, as the literature suggests (Håkansson et al., 2021; IPCC, 2019). The chamber method was used, and all the measurements were made during the day between 7:00 hrs - 15:00 hrs. The chambers were placed in the fertilization area of the coffee plant. All agricultural practices applied to the coffee plantation during the experimental phase were maintained following traditional farm management. These included weed control, shade regulation, and applying any chemical products used to control phytosanitary problems. Harvesting was also carried out by regular farm management. The density in the farms was 4022 plants per hectare, with a distance of 0.75 between each plant per row. The varieties were (Catuai and Geisha, with 15 to 20 years of planting in the lots measured, and the shade-regulated plant tree *(M. paradisiaca L.),* and Coral trees (*Erythrina; L),* as is shown in figure 2-8.

Figure 2 - 8: Field measurements and monitoring in Costa Rica.

2.2.3. Implementation and monitoring

During the first tests carried out on the farms within the cooperative, different blocks were randomly selected within the plot of the Research Center for the Development of Organic Alternatives (CEDAO), where the most significant number of analyses were carried out due to the continuous monitoring of fertilization. The measurements were made to compare the dates of fertilization, the climatic characteristics of the date, and the relationship of the fertilizer emission throughout coffee cherries production in plantations. Table 2 - 1 below shows the fertilization process for the blocks first studied for nitrous oxide measurement. This area includes nine lots with an area of approximately one hectare. The variety of coffee plants is centered only on the Catuai species, having a total amount in that area of approximately 4022 plants with a planting age between 15 and 20 years old.

Table 2 - 1: Fertilization formulas and applications at the coffee plantations.

Types of Fertilizers used (90 g per plant)		
Chemical Fertilizer*	**Chemical Fertilizer****	**Physical Fertilizer*****
17 (N) - 6 (P_2O_5) - 18 (K_2O) - 5 (MgO) - 0.2 (B) - 0.1 (Z) - 1.6 (S)	20 (N) – 8 (MgO) - 11 (Ca)	18 (N) – 5 (P_2O_5) – 18 (K_2O) - 0,2 (B) - 7,3 (S)

* Used twice per year: June, August, ** Used once per year: October, *** Used once per year: May

2.2.4. Fertilization trials

A fertilization trial was suggested to understand which fertilizer produced higher N_2O emissions when added simultaneously. Figure 2 - 9 shows how the fertilization trial was tested (the figure shows just one row of duplicates performed). In addition, a physical fertilizer was compared with a chemical fertilizer and compost as a soil amendment produced during this study using coffee by-products and green waste. Finally, all of these are compared to control following the typical fertilizer of the crop year.

There are simple and complete fertilizers, which differ in their concentration of essential plant nutrients. A simple fertilizer contains only one of the essential primary elements, such as urea, potassium chloride, and magnesium oxide. When a fertilizer contains more than one essential nutrient, such as 15 - 15 – 15; 17 - 6 - 18 – 2; and 25 - 4 - 24 of N, P, and K, it is classified as compound fertilizer, and there are two types. The first type of fertilizer is a complex/complete or chemical compound fertilizer (Sadeghian-Khalajabadi et al., 2007). These are the results of chemical reactions of ingredients or raw materials, with the advantage of each individual having the same chemical composition and thus ensuring the proportionality of nutrients when applied to plants. The other category is known as physical compound fertilizer. These are created by physically or mechanically mixing two or more fertilizers. Physical mixtures are at risk of component segregation (separation), resulting in a heterogeneous distribution of nutrients along the planting line. There is no transformation because there are no chemical reactions, and there is not enough pressure to shatter the raw material particles. Therefore, each particle preserves its physical and chemical characteristics after mixing (Gobierno De El Salvador, 2020; ICAFE, 2011a).

The main reason for the comparison is that both fertilizers are used on coffee plantations during the production and growth cycle. It was taken into account to start the experiment a month before the year's fertilization started. The gas collection was carried out considering that the highest N_2O emissions occur during the first days after fertilizer application (typical of conventional fertilizers). Lack of information for this type of production system regarding the N_2O generation derived from fertilizers and their application; therefore, it is crucial to understand the behavior of the fertilizers and obtain the first emissions fluxes. In the present experiment, given the fertilizer application, the collection of gas samples continued for a more extended period (two harvest cycles) since there is no information available for this production system regarding the generation of N_2O derived from the application of fertilizers.

Figure 2 - 9: Fertilization trials in Costa Rica.

2.3. Composting emissions measurement technique

The focus was on whether the different treatment methods for coffee by-products could be comparable or compatible with each other in terms of gaseous emissions. Therefore, the selection of the measurement method should allow for comparable data on the various types of treatment and methane concentrations. A third consideration for selecting measuring instruments was the compact design of the instruments for easy transport. Therefore, some tests were performed before the composting process finished (W. Brinton et al., 1995). The Dewar method is essentially a standardized method for assessing self-heating. Self-heating is important because it drives the composting process, and the presence of heat in compost, regardless of other characteristics, is a sign of immaturity. Compost self-heating in a Dewar bin is a respiration technique that yields similar results to CO_2 respirometry measured over 3 to 7 days. This means that the heat generated by the Dewar test is produced by the compost materials' respiration (Pecorini et al., 2020).

On the other hand, before the measurements, in a selected study area, the time of the measurements was performed until the emissions remained permanently constant. Therefore, no variation during the measurements could occur. During the sampling and measurement of emissions in the pilot in Germany, the idea was to corroborate the emissions and measurement technique. In this case, the gas collection was done using a bag made of Nalophan, which is the standard norm in odor monitoring (VDI 3880, 2011). With this flexible sampling method, gas samples can be taken from many sources (active and passive sources), and gas quantification can be performed with the available devices (VDI 3880, 2011).

The portable device used in Costa Rica, a Multitec 540 from the Sewerin©, is used to measure CH_4 concentrations using a chamber technique. One of the advantages is the infrared light for methane detection, eliminating distortions of the measured values caused by cross-sensitivity with other gases (Sewerin, 2018). According to the manufacturer, the methane measurement range within the equipment goes from 0-100 % vol (0 - 1000000 ppm ± 5% SD of the sensitivity and ± 1.5 % error percentage). The measurements were carried out weekly and before any mechanical pile turning. This was made during the first five weeks of the composting process. After that, emission rates are quantified using the flow-through sampling chamber principle and related to the compost's treatment and quality.

2.4. Coffee plantations emissions and measurement technique

The main focus was to compare gaseous emissions and the different treatment methods for coffee by-products. Therefore, selecting the measurement method should allow for comparable data on the various types of treatment and nitrous oxide concentrations. Another critical point to consider for selecting was the easy transport of a measuring device and placing it among the coffee plantations since the coffee trees are usually based in the mountain area. Furthermore, before the measurements, in a selected study area, the duration of the measurements was estimated. The duration estimation was considered until the emissions remained permanently constant; therefore, no variation during the measurements could occur by the sample principle used during CH_4 measurements during composting.

The chamber method was used for the coffee plantation N_2O gas and CH_4 measurements. This method is easy to build, use, and inexpensive to estimate the concentration changes of gases coming from the soil in a defined time and volume (J. Wu et al., 2009). The chamber was placed on the surface of the soil using the chamber soil collar or soil frame and was pressed to ensure that no gaseous exchange (entering or exiting the chamber) occurred at the edges, as is shown in figure 2 - 10.

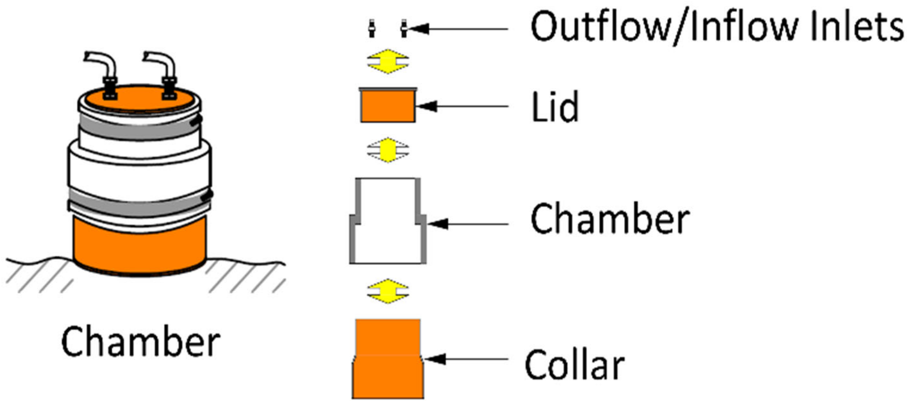

Figure 2 - 10: Chamber design.

A Gasmet DX4040 portable FTIR gas analyzer was used during the experiments and measurements. This device identifies multiple gas compounds (up to 50) from samples under difrerent ambient conditions. In addition, the device uses the software "Calmet" (algorithm), which allows analyzing the concentrations of different components throughout visualizing the FTIR spectra of the sample collected (Gasmet Technologies, 2017).

2.5 Emissions fluxes

It is important to estimate GHG emission rates as they are the flow of a pollutant expressed in weight per unit of time (Daelman et al., 2012; Kirschbaum et al., 2006). Therefore, detecting gaseous emissions during composting coffee by-products is one of the essential tools to meet the challenge of reducing GHG emissions and odor emissions.

The emission rates of the gas (CH_4 and N_2O) were calculated based on: sampling chamber volume, sampling chamber area, the flow volume of the measurement equipment, specific flow rate, and correlation factor for each measurement performed. The following equations describe the calculations and general formulas used to obtain the emission rates during the study.

$$C_{gas} = (M_{gas} * \varphi_{gas})/V_{mol} \quad (1)$$

C_{gas} : Gas Concentration, Unit: mg/m³
M_{gas}: Molar mass of gas, Unit: g/mol
V_{mol}: 22,4139 L at Standard Conditions
Φ_{gas}: Volume percentage of gas in air, Unit: ppm

Emission rates

$$Q_{gas} = (C_{gas} * V_{gas}) / A_H \quad (2)$$

Q_{gas} : Emission rate of gas, Unit: g/(m² x h)
C_{gas} : Gas Concentration, Unit: mg/m³
A_H : Hood area, Unit: m²
$V_{gas\ device}$: Gas Flow volume, Unit: L/h

2.6. Emission Factors

Emission factors (EF) are specific parameters related to a reference variable describing the process (Vergara & Silver, 2019). When the measurement data is known from the literature, they allow the source strength of an existing facility to be deduced. The emission rate is necessary to calculate an emission factor. The representative value attempts to relate the amount of a pollutant released into the atmosphere with an activity associated with releasing that pollutant (Cheremisinoff, 2011).

The United States Environmental Protection Agency defines an emission factor as: "*A representative value that attempts to relate the amount of a pollutant released into the atmosphere to an activity associated with the release of that pollutant. These factors are* *generally expressed as the weight of the pollutant divided by the unit weight, volume, distance, or duration of the activity emitting the pollutant"* (EPA, 2009).

EF was calculated during the composting process and open field depositions for this study. The variable reference where the EF is calculated in this study relates to the mass of coffee pulp treated and compared to the literature regarding composting. Therefore, the EF is calculated as follows:

$$EF_{CH4} = (q_{CH4} * t_{treat} * A_{treat}) / m_{treat} \quad (3)$$

EF_{CH4}: Emission factor of methane related to the mass of coffee pulp treated, Unit: g/kg

q_{CH4}: Emission rate of Methane, Unit: $g/(m^2 \times h)$

t_{treat}: Duration time of treatment, Unit: h

A_{treat}: Area of treatment (surface area of the emission), Unit: m^2

m_{treat}: Mass of treated material (mass of coffee pulp at the pile), Unit: kg

The emission factor is usually expressed per ton of treated waste or obtained compost. The only emission factor to date regarding composting in Costa Rica is 4 g CH_4/kg waste given by the National Meteorological Institute of Costa Rica (IMN, 2021). Nevertheless, the methodology and type of waste are unknown. This is one reason why urges to obtain emission factors, specifically with the type of input used and emission factors related to the composting process in agriculture. Hence, this study can collect the first data and generate the first emission factors related to the coffee waste during the composting process in Costa Rica.

3. Publication I: Enhanced composting as a way to a climate-friendly management of coffee by-products

The content of this section has been published in the scientific journal *Environmental Science and Pollution Research*: San Martin Ruiz, M., Reiser, M. & Kranert, M. Enhanced composting as a way to a climate-friendly management of coffee by-products. *Environ Sci Pollut Res* 27, 24312–24319 (2020). https://doi.org/10.1007/s11356-020-08742-z

3.1 Abstract

This study investigated the performance of aerobic windrow systems by using coffee by-products and green waste to reduce gaseous emissions. Thereafter, a comparison with the current treatment and gaseous emissions at a Coffee Mill in Costa Rica was made. Two different studies were performed in Germany (pile I and II) and one study in a Coffee Mill in Costa Rica (pile III). Temperature, water content, and pH were the key parameters controlled over 35 days in all the systems. Moreover, CH_4 emission rates were quantified by a FTIR and by a portable gas detector device where the emissions reached values 100 times higher when coffee by-products as a unique material for the composting process was used. Results show that highest emission rates during the composting process for pile I was 0.007 $g(m^2)^{-1}\ h^{-1}$, for pile II 0.006 $g(m^2)^{-1}\ h^{-1}$, and for pile III 3.1 $g(m^2)^{-1}\ h^{-1}$. It was found that CH_4 emissions could be avoided if the mixture and the formation of the windrow piles were performed following the key parameter for composting, and the usage of additional material is used. With this, the reduction of CH_4 emissions at the Mill in Costa Rica could be achieved in the future.

Keywords Composting, Coffee by-products, Coffee pulp, Methane, Emission rates, Greenhouse gases.

3.2 Introduction

Composting among the years has become a promising natural way of recycling organic matter and producing fertilizer under low operating costs and minimal technology (Haug 1993; Misra et al. 2003). It is defined as “a biological decomposition and stabilization of organic substrates, under conditions that allow the development of thermophilic temperatures as a re- sult of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seed and can be beneficially applied to land” (Artola et al. 2015; Misra et al. 2003). The base of composting is not the complete decomposition of the input components but rather to prepare a biologically stable material which is not exposed to a process of rapid decomposition or undesirable rotting (Burg et al.2011). During the process, temperature has been one key factor in composting which has been used as a tool to follow the degree of stabilization as a result of microbial activities during the process (Bueno et al. 2007). One of the disadvantages of composting is the formation of greenhouse gases (GHG) such as methane (CH_4) that enhance the global warming (Zhu- Barker et al. 2017). The GHG formation occurs from the ac- activity of microorganisms during the composting process (Sun et al. 2014). CH_4 corresponds to the main product when the windrow piles do not receive the necessary oxygen at the core of the windrow (Amlinger et al. 2008). In the agricultural sector, GHG represents 24% of the total emissions globally, excluding carbon dioxide (CO_2) since the gas generated is climate-neutral carbon, for the reason that it originate from the conversion of organic material and dead organic matter (Amlinger et al. 2008; Sun et al. 2014).Currently, the Mill of study in Costa Rica is treating its coffee residue to produce compost, where the main material is based on coffee husk and coffee pulp as coffee by-products (Zarrinbakhsh et al. 2016).

During the wet process of coffee bean extraction, these coffee by-products are divided into coffee husk, skin, pulp, mucilage, and parchment (Esquivel and Jiménez 2012; Iriondo-DeHond et al. 2019). The main coffee by-product obtained during wet or semi-dry processing is the coffee pulp, which corresponds to approximately 29% on a dry-weight basis (Blinová et al. 2017; Heeger et al. 2017), where one ton of coffee pulp is generated for every two tons of green coffee produced (Esquivel and Jiménez 2012). Coffee pulp is an organic waste that contributes to pollution and environmental problems when the coffee berries are ripe and processed during the wet method (Lardé 1989; Blinová et al. 2017). In each harvest at this Mill in Costa Rica, where wet process is the main method to process the coffee cherries, the coffee by-products produced are approximately 37,000 Mg/year.

Understanding greenhouse gas emissions formation is an important criterion in future evaluation options for climate change mitigation within the coffee sector (Rahn et al. 2014; Nieters et al. 2015). Coffee by-products are also the contributors to climate change as a result of their greenhouse gases emitted (Rahn et al. 2014); therefore, their emissions play an important role.

In this study, first a characterization of coffee by-products and green waste products was completed. Based on this, it was proposed to carry out a pilot plan in Germany with different green waste materials and coffee pulp to investigate the behavior of this coffee by-product during the composting process for 35 days. In addition, to determine the capacity to reduce greenhouse gases emissions and other harmful impacts on the environment, a comparison with the current composting process at the Mill in Costa Rica and the composting process which was performed in Germany were made.

Finally, the quantification of CH_4 emission rates in three different piles containing coffee pulp as a main component was performed to analyze the relevance of external materials and their relationship with the current CH_4 emissions within the usage of coffee pulp during composting.

3.3. Materials and methods

3.3.1. Windrows description

Composting profile, chemistry, and greenhouse gas emissions were monitored at the composting plant facility in Germany and at the Mill in Costa Rica. The coffee pulp was sundried at the Mill and shipped to Germany. Once it arrived in Germany, naturally the material was humidified until the fresh percentage that the fruit possess. On the other hand, the green waste for the experimental site in Germany was obtained from the composting plant facility where the windrows were built. Three windrow piles were monitored in total, and the main component was the coffee by-product.

The first pile (I) was formed using 50% based on volume of coffee pulp, a mixture of 50% based on volume of green waste, and a structural material at the composting plant facility during the winter season. Pile II was formed using 20% more based on volume of coffee pulp than in pile I, a mixture of 30% based on volume of green waste, a and structural material composted during the spring season, whereas pile III was completely made with coffee by-products during the summer season using the current methodology of the mill at the Mill in Costa Rica. Two windrows piles (I and II) were monitored in Germany and afterwards compared with the current emissions obtained from a previous study (San Martin Ruiz et al. 2018). The piles were running for a period of 35 days, taking into account the specifications at the composting plant facility to produce compost using green waste material as an input. The material was turned weekly using a Tracturn® windrow turner at the composting plant facility and in Costa Rica with a Backhus® windrow turner. The sizes of the piles in Germany were approximately 6 m^3, while in Costa Rica, the pile was approximately 90 m^3 with 1.2 m high and 2.2 m wide for all the piles.

Table 3 - 1: Constituents of input material for each windrow pile.

Windrow system	Material	C/N	pH	κ mscm^{-1}	WC %	DS %	$ρ_t$ g/L	VS %
				Input Material Germany				
I and II	Humidified coffee pulp	20±0.2	6±0.1	1.1±0.1	79.7±0.2	20.3±0.2	564±6.0	90.9±0.4
I	Green waste[1]	22±0.1	5±0.1	2.0±0.4	21.3±0.2	78.7±0.3	505±5.0	98.1±0.1
I	Structure Material[2]	28±0.3	6±0.1	0.9±0.1	25.8±0.2	74.2±0.1	232±3.0	67.8±1.3
II	Structure Material[3]	67±0.5	6±0.1	0.4±0.3	31.8±1.2	68.2±0.8	190±5.0	77.2±0.1
II	Green waste[4]	31±0.1	7±0.2	0.7±0.2	35.8±0.0	64.2±0.5	550±5.0	53.6±0.2
				Input Material in Costa Rica				
III	Fresh Pulp	13.4±0.2	3.9±0.1	1.6±0.1	84.9±0.2	15.1±0.7	600±10.0	88.9±1.8

[1,2:] Green waste and structural material during winter season in Germany 3,4 Green waste and structural material during spring season in Germany Standard deviation of the mean values n = 3 for all the values.

Gas samples were collected weekly before each turning event. Compost samples were collected before and after each turning event. Temperature was measured continuously using an Armatherm thermometer® T-logger in pile I and II. On the other hand, at the Mill, the temperature was measured twice a day during the mornings and afternoons using a compost thermometer and the samples for the key parameters were collected weekly.

3.3.2. Compost sampling and analyses

Compost input material which was used to form the windrow piles in Germany were sampled to quantify the gravimetric water content (WC), pH, electrical conductivity (κ), bulk density (t), dry solids (DS), volatile solids (VS), and carbon to nitrogen (C/N) ratio which are shown in Table 3-1. Once the windrow piles were formed, WC, pH, and C/N ratio were performed weekly. The samples were collected before and after each turning event and were taken from 5 different locations and depths along the pile to obtain a representative sampling over the entire pile. Water content was calculated from field moist and oven-dry (105 °C for 48–72 h) mass of compost according to the DIN EN 13040 (BGK 2017). The pH was extracted from 20 g (wet weight) of compost with 180 mL of $CaCl_2$ and assessed by potentiometric measurements.

Electricity conductivity was extracted from 20 g (wet weight) of compost with 180 mL of distillated water. Volatile solids were performed and calculated according to the Federal Compost Quality Assurance Organization (FCQAO) (Bidlingmaier 2003) and according to the DIN 18128. C/N ratios were performed using a Vario Max CN element analyzer GmbH® following the DIN ISO 10694.

For the VS, three replicates of 10 g were inserted into a porcelain crucible with known weight. The samples were inserted into a furnace at 550 °C and burned until constant weight according to the DIN 18128. Thereafter, the volatile solids were calculated for each replicate, and the average of the three values was taken to represent the organic content of the sample.

3.3.3. Gas measurements and collection

At the composting plant facility in Germany, an open upper part chamber was placed on top of the windrow piles and inserted approximately 5 – 10 cm deep into the windrow to seal the chamber against atmospheric influences in order to quantify the windrow emissions focusing on CH_4 measurements. At each sampling event, the sample was taken from at the top of the windrow pile since the main emissions are emitted at this area of the pile (Ahn et al. 2011).

Figure 3 - 1: Gas measurement at the composting plant facility.

During sampling, the flow principle passing through the sampling hood at a passive area source was used to extract a defined amount of air (open upper part chamber), covering the entire area required for sampling as a function of the constant flow of emissions and supply of ambient air (Bidlingmaier 2003; VDI 3475 part 2 2005). The sampling device consists of a vacuum vessel which is discharged by using a vacuum pump, and at the same time, a hose is connected between the open upper part chamber and the vacuum vessel to collect the gas.

When the sampling device begins pumping, the sampling bag, made of Nalophan, absorbs the inner gas (Fig. 3 - 1). The upper part was uncovered allowing the ambient air to enter and to be mixed inside of the sampling hood. The gas collection was done weekly for a period of 30 min in order to collect 6 L of gas in a sampling bag. The gas samples were analyzed using Fourier-transform infrared spectroscopy (FTIR). Thereafter, the gas measurements were compared according to the previous study performed at the Mill in Costa Rica, where an open upper part sampling hood was used to measure the gas concentration by using a portable gas detector device (Fig. 3 - 2) (San Martin Ruiz et al. 2018).

Figure 3 - 2: Gas measurement at the Mill in Costa Rica.

3.3.4. Emission rates

The emission rates were calculated according to the sampling chamber volume, sampling chamber area, flow volume of the measurement equipment, and a specific flow rate each measurement performed. The following equations describe the calculations and formulas used to obtain the emission rates (Clauß et al. 2019; San Martin Ruiz et al. 2018).

$$C_{CH4} = (M_{CH4} * \varphi_{CH4}) / V_{mol} \quad (1)$$

C_{CH4} : methane concentration, (mg/m³)

M_{CH4}: molar mass of methane, (g/mol)

V_{mol}: 22,4139 L at standard conditions

φ_{CH4}: methane in volume percentage or in ppm.

$$q_{CH4} = (C_{CH4} * V_{gas}) / A_H \quad (2)$$

q_{CH4} : emission rate of methane, (g/m² h)

C_{CH4} : methane concentration, (mg/m³)

A_H : hood area, (m²)

V_{gas}: gas flow volume, (l/h)

3.3.5. Statistical analysis

In total 25 gas measurements during morning and afternoon were performed at the mill in Costa Rica, obtaining up to 5 replicas among the pile. The data for pile III was subjected to one-way analysis of variance ANOVA for Windows. Significant level of $p \leq 0.001$ for pile III was used for all mean values. Meanwhile for piles I and II, measurements were per-formed once per week. Nevertheless, a 2% linearity deviation was considered for the results.

3.4. Results

Figure 3 - 3 shows a summary of the input features of the compost material measured when the windrows were built. All three piles were having triangular shape, width, and height where the only difference was the length of the pile, and this was due to the viability of coffee pulp material shipped to Germany. Therefore, pile I and II were shorter than at the Mill in Costa Rica. After receiving the dehydrated coffee pulp, certain analyses were carried out to estimate the amount of water necessary to humidify the pulp and with this, to be able to carry out the simulation of fresh material at the composting plant facility in order to follow closely and in a real sense how the coffee by-products are handled at the mill in Costa Rica. As can be seen in Table 1 - 1, the hydrated material obtained a difference of 5 percentage point with respect to the percentage of original moisture. C/N ratio have increased during the humidification of the coffee pulp, which indicates that during the drying process, the material had a nitrogen transformation; therefore, the C/N ratio increased as well as its pH (Hao and Benke 2008). All the previous analysis indicates that the preliminary results are significant for the study and a comparison between the systems can be made.

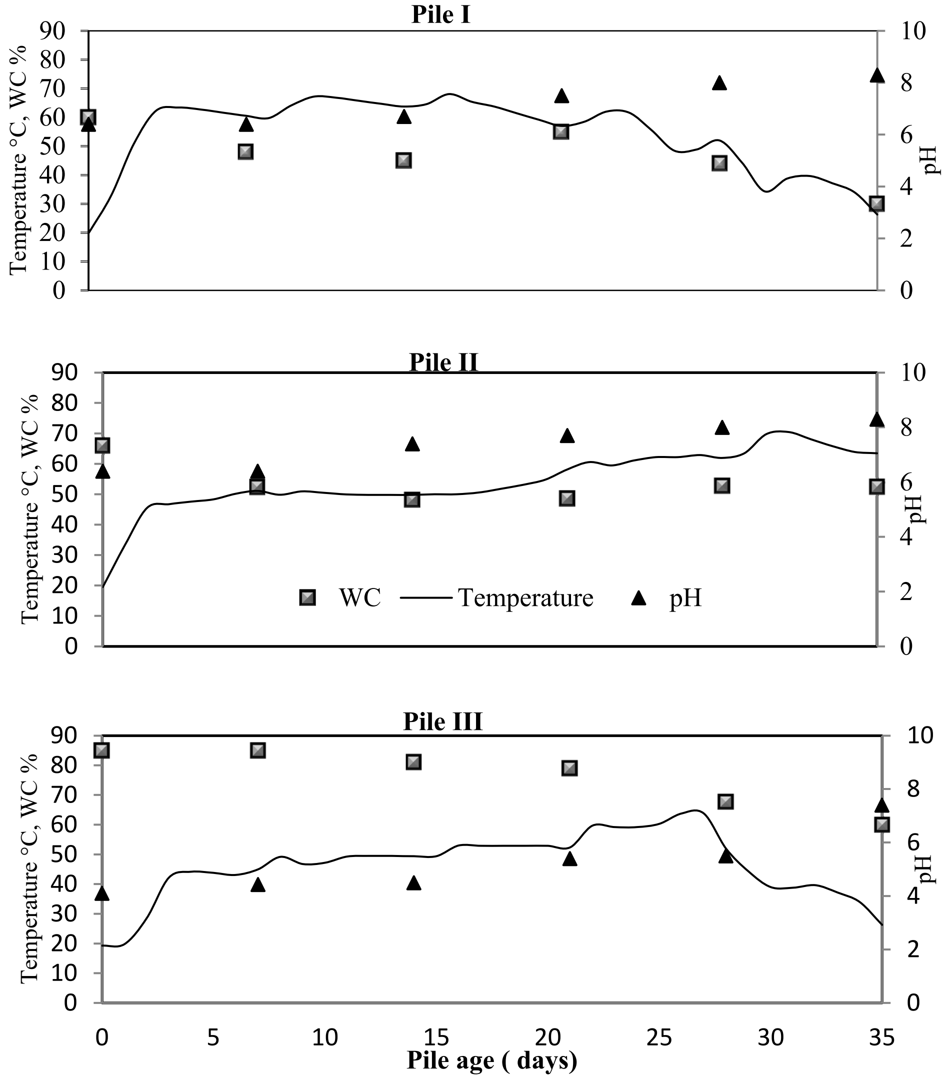

Figure 3 - 3: Temperature, water content concentration, and pH in three piles.

3.4.1. Parameters and temperatures profiles in composting windrows

All the temperature data from the T-logger was given weekly from the personnel of the composting plant facility whereas in Costa Rica, the temperature was measured twice per day (mornings and afternoons). The composting process was performed during different times of the year; therefore, the feedstocks of each pile were based on the available material that the composting plant facility had during that season in addition to the piles experiencing different seasonal conditions. Pile I experienced a winter climate with an average ambient temperature of 5.4 °C. Pile II experience a spring climate season between 13 and 18 °C. Pile III accomplished a summer climate at the Mill in Costa Rica, where the range of ambient temperature was 28 °C without any rain event. Significant temperature increases were observed between the windrow systems. Pile I and II were performed in a place covered by a roof, while pile III was performed in an open field at the Mill. Generally, the temperature was higher where a high percentage of green waste was added, reaching rapidly 60 °C within the first week even if the windrow system was performed during winter season and under low ambient temperature. Figure 3 - 3 shows that WC decreases among the pile age of the windrow systems I and II, whereas in pile III occurred no variation during 20 days of pile age, and the high value is attributed to the high WC of the coffee by-product. It is important to control the degree of degradation during the composting process, because this parameter is used to give information regarding the decomposition process (Burg et al. 2011). Compost microorganisms work best under neutral rather than acidic conditions (Sundberg 2008), where at pH levels under 5, the microorganisms' inhibition can be noticed (Bachert and Wattanachira 2008; Sundberg et al. 2013). Organic acids are neutralized within the process, and mature compost generally has a pH between 6 and 8 (Burg et al. 2011; Sundberg 2008). The pH increased in pile I and II over the pile age, while pile III remained acidic. Pile I and II where carried out under a C/N ratio of 25:1 and 30:1, respectively. The WC in pile I had a rapid evaporation or absorption within the material during this process. No water was added into pile I in order to maintain the humidity from the pile itself. In pile II, the WC was between 30 and 60% during the pile age, where incorporation of small amounts of water was needed to maintain a WC between 40 and 55% until the sanitation process occurred. Pile III maintained moisture between 40 and 66% itself during the total process, and no additional water was added during the process in 35 days.

3.4.2. Methane emissions from compost windrow piles

All the CH_4 emissions were measured before each turning event at the pile in order to achieve the similar conditions for a congruent comparison between the systems. During the conversion of methane concentration to emissions rates (ER), the flow through the upper part chamber was considered. Figure 3 - 4 shows the results of emissions rates over the pile age represented in weeks for the three different windrow systems. The emission rates in pile I and II were reduced drastically in comparison with pile III.

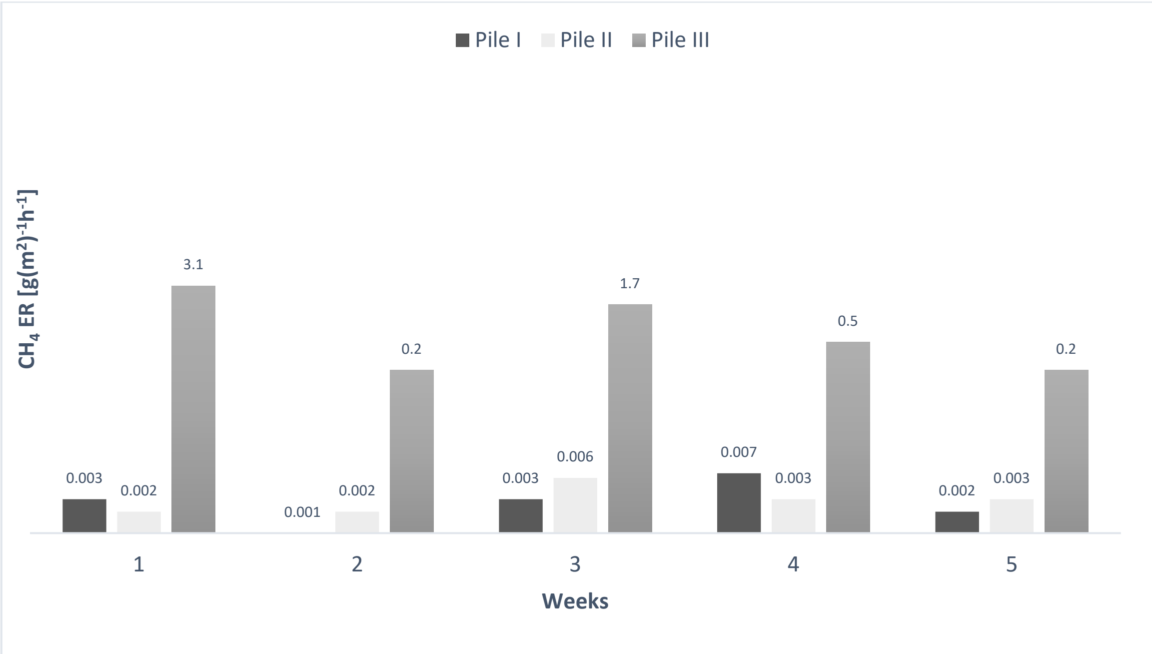

Figure 3 - 4: CH_4 emission rates (ER) [g$(m^2)^{-1}$ h^{-1}] from the windrow piles plotted with the logarithmic scale to the number of weeks of the process.

However, the pile II had obtained an increase of CH_4 emissions in comparison with pile I. This can be related to the amount of coffee pulp increased a 20%. The maximum values of CH_4 emission rates in pile I were found during the fourth week, pile II during the third week, and pile III at the first week of composting which can be related to the poor aeration and high WC levels (85% of WC reported during the first week in pile I), enhancing the methane formation (Amlinger et al. 2008; Hrad et al. 2014; Jenkins 2011; VDI 3475 part 3 2006).

3.5. Discussions

Firstly, the attention was focused on the fact that the amount of green waste and coffee by-products for the composting could be comparable to each other in terms of gaseous emissions and that the additional material would be easily accessible and collected. Therefore, the selection of measurement methods had to allow comparable data in the various types of treatments, as well as CH_4 emissions. Temperature profiles show that after increasing the addition of coffee pulp into the windrow pile, the temperature will take up to 25 days to reach the sanitation peak (Diaz et al. 2007; Jenkins 2011).

On the other hand, the temperature at any point depends mainly on the amount of heat produced by microorganisms and the amount lost through aeration and surface cooling. Therefore, the time where the system remains with high temperatures will depend on the chemical composition of the ingredients, as well as the volume of the system. During the thermophilic stage (40–60 °C), the degradation occurs faster and can take from days to months depending on the material and the composition of the ingredients (Cornell University 2001; Sierra et al. 2017; VDI 3475 part 2 2005). This stage of composting contains a relevant path in order to destroy germs that are sensitive to the temperature (Msunar 2009; Sierra et al. 2017; VDI 3575 part 1 2003). In pile I and II, the thermophilic stage starts during the first 2 days of composting, while pile III needed more days to achieve the mesophilic phase. During the first phase of the process, the pH value tends to drop due to liberation of organic acids.

Thereafter, once the process is moved to the next phases, the pH value tends to rise since all the organic acids are broken down as well as the alkaline effect of the inorganic salts which tend to be bonded to the organic material. At the end of the phases, the pH value must fluctuate in the neutral to basic range (Kranert 2017; VDI 3575 part 1 2003).

During the composting process, high temperatures in the windrow pile kill worm eggs and pathogens resulting in a compost sanitation (Bidlingmaier 2003; Federal Compost Quality Assurance Organization 1994; VDI 3475 part 2 2005) which were reached by pile I during the first days of composting whereas in pile II and III after 20 days of composting time. An optimal C/N ratio for the development of microorganisms and bacteria responsible for composting is between 25:1 and 40:1 (Ahn et al. 2011). Based on this, the piles at the composting plant facility followed the appropriated ranges of C/N during the process.

Three important factors that affect the temperature change are the WC, sufficient oxygen in the windrow pile, and the shape of the pile. The pore-volume relationship during the process is an important prerequisite in order to enhance a good composting process. If the material does not possess enough oxygen and high amount of water content, the low air pore volume in the pile is being affected, and therefore, a release odor due to anaerobic metabolites occur. Triangular shape results in a larger surface-to-volume ratio, giving a natural convection allowing adequate aeration (VDI 3575 part 1 2003). Giving an adequate moisture level, which was given in pile I and II, the microorganism activity is maintained for a longer period. Low water content in the decomposition material may partially or completely inhibit the activity and reproduction rate of the microorganisms (dry stabilization) (Jenkins 2011; VDI 3475 part 2 2005). The recommended WC at the beginning of the windrow pile is 50 – 60%, finishing the composting process with approximately 30% (Haug 1993; Misra et al. 2003; Sierra et al. 2017; VDI 3575 part 1 2003). In pile I, the WC at the beginning was around 60% and pile II was 66%. Since pile I experienced an early drying process, it was preferable to start with a higher WC value, which after 7 days, the windrow pile had reached the recommended value for the composting process. Pile III, on the other hand, kept a high WC value from the beginning until the last days of pile age. In the case of the coffee pulp, if its water content is comparatively low in porosity below 20 – 25% or above 60%, the aerobic process is stopped (Bidlingmaier 2003; Esquivel and Jiménez 2012; VDI 3475 part 3 2006). Above 60%, due to the dense structure of the coffee pulp (Table 1 - 1), it tends to keep high moisture content within if the material is not mixed or aerated regularly nor when there is no structural material in the windrow pile. The addition of structural material increases the volume of pore and therefore improves the exchange of water and air (Clausen 2015; Sánchez et al. 2015). Hence, structural material was considered in pile I and II to perform this work. Pile II, for 5 weeks, did not decrease the temperature profile, reaching the sanitation process during the last week, whereas pile III, after 5 weeks, decreased in temperature indicating less microbial activity. Therefore, coffee pulp needs proper WC, pH, oxygen, and porosity to reach a higher degradation. In addition to temperature measurement, the degradation of organic dry matter showed a rate approximately of 50% for pile I, 55% for pile II, and 34% for pile III.

On the other hand, detection of gaseous emissions is an essential measure for assessing the rotting process in terms of aerobic status and environmental relevance. On this basis, greenhouse gas and odor emissions can be reduced through optimized rotting management. The detection of gaseous emissions during the process of composting coffee by-products is one of the most important tools to meet the challenge of reducing GHG odor emissions in this sector. Gas concentrations act as indicators of a biological degradation and thus lead to optimization possibilities. Regarding the CH_4 emission, previous studies show it is linked to the micro- organisms' activity and also connected to pH and temperature (Zhu-Barker et al. 2017). During the process, the pile I and II follow the recommendations and moisture content profile of a proper composting process, while pile III maintains a high WC during the 35 days leading to constant CH_4 emissions. It was seen that during the first week, pile III obtained the higher emissions, which might be linked to the amount of water content (85%), and lack of oxygen due to the compactness of coffee by-product.

During these measurements, the gas measured was CH_4 since it is produced and oxidized during the degradation of organic matter with low O_2 content and during the biological activity of the windrow pile (Phong and Cuhls 2016). CH_4 formation is a product of anaerobic degradation forming organic acids as a result of methanogenesis (Hou et al. 2017; Msunar 2009). Since this gas is formed during endothermic reactions, and also when aerobic piles develope anaerobic zones inside of the pile during the composting process, this gas produce a reduction in the microorganism activity and as a consequence, CH_4 emission (Phong and Cuhls 2016; VDI 3475 part 2 2005; VDI 3475 part 3 2006).

It is recommended in order to increase the porosity, oxygen, and decrease of emissions in the pile, the addition of green waste, branches or woodchips into the system, as well as the control of WC and temperature within the process. It was seen in pile III which possessed just coffee by-products, emissions up to 100 times higher than in pile I and II, where green waste and structural material was incorporated to give porosity to the windrow piles at the composting plant facility.

3.6. Conclusions

Aerobic composting windrows were performed by using coffee by-products as a main component in a composting plant facility and were compared with the current treatment at the Mill, showing better profiles of temperature, pH, and WC when coffee by-products are mixed with green waste to form windrow piles.

Emission rates were determined and given in [$g(m^2)^{-1}$ h^{-1}]] based on the methodology described and compared with the emissions at the Mill in Costa Rica. CH_4 emission rates were lower in pile I and II than in pile III where the highest emissions rates for 35 days found in pile I was 0.007 $g(m^2)^{-1}$ h^{-1}], in pile II 0.006 $g(m^2)^{-1}$ h^{-1}], while in pile III showed an emission of 3.1 $g(m^2)^{-1}$ h^{-1}].

It was found that CH_4 emissions could be avoided if the mixture and the formation of the windrow piles are done following the key parameter for composting, and therefore, the treatment at the Mill have the option to improve and to reduce the GHG emissions, giving the opportunity at the coffee sector during the management of the coffee by-products to improve the management of coffee by-products and to obtain a material with low emissions to be used afterwards in the coffee plantations as a fertilizer.

Acknowledgments Open Access funding provided by Projekt DEAL. We acknowledge the support, funding, and assistance of this work by the Coffee Mill Cooperatarrazú R.L in Costa

Rica. We gladly thank the composting plant facility Abfallwirtschaftbetrieb Landkreis Böblingen as well as the personnel, laboratory assistances, students, and colleagues of the Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) at the University of Stuttgart.

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4. Publication II: Composting and Methane Emissions of Coffee By-Products

The content of this section has been published in the scientific journal *Atmosphere*: San Martin Ruiz, M.; Reiser, M.; Kranert, M. Composting and Methane Emissions of Coffee By-Products. *Atmosphere* 2021, *12*, 1153. https://doi.org/10.3390/atmos12091153

4.1. Abstract

In the last 20 years, the demand for coffee production has increased detrimentally, heightening the need for production, which is currently driving the increase in land cultivation for coffee. However, this increase in production ultimately leads to the amplification of waste produced. This study aims to develop an experimental methodology for sustainable coffee by-products (Pulp (CP)) in Costa Rica for nutrient-rich compost. The performance of the experiments is to explore and optimize composting processes following its key parameters. This will allow quantifying the emissions rate to obtain an emission factor for CP during the open composting process and optimizing the conditions to minimize CH_4 emissions using P and green waste (GW) materials. Five CP and GW mixtures were analyzed for the composting process for ten weeks, acting P as primary input material as a by-product. Quantification of the methane emissions was performed in two areas: composting area and open field deposition. Peak temperatures of compost appeared at twenty-five days for control and five days for GW added treatments. CP emission factors provide a similar result with the standard values recommended by the literature, accomplishing the emission reductions. Thus, this study designed and validated a sustainable protocol for transforming coffee by-products into compost.

Keywords: coffee pulp; coffee by-products; composting; methane; emissions rate; emissions factor

4.2. Introduction

Agriculture is responsible for an essential portion of global emissions, contributing to 45% of their methane (CH_4) emissions globally, impacting climate change [1]. In addition, gas concentrations act as indicators that show biological degradation, and this guides optimization possibilities of developing new strategies for emissions reduction [2]. Therefore, it is required to estimate greenhouse gas (GHG) emission rates as they are the flow of a pollutant expressed in weight per unit of time [3]. Emissions rates are necessary to calculate an emission factor, a representative value that attempts to relate the amount of a pollutant released into the atmosphere with an activity associated with the release of that pollutant [4]. The detection of gaseous emissions during composting coffee by-products is one of the most critical tools to meet the challenge of reducing CH_4 emissions from the waste residues generated in the coffee processing industry [5,6]. Coffee is a worldwide used product and of the most valued commodities in trade, being one of the most important agricultural exports in Costa Rica [7]. In coffee processing, the production chain comprehends several steps. Firstly, the berries from the coffee plants are transported to be washed and peeled (de-pulping), separating the green beans from the pulp or husk [8]. The outer membrane that envelops the coffee bean is called the pulp (CP) (mesocarp), which contains 43% *w*/*w* of the morphology of the coffee fruit [9–11]. CP is one of the main by-products generated during the process [11]. It contributes to pollution, environmental and health problems of the surrounding waters, soil, and atmosphere when the coffee berries are ripe and processed during the wet method and mishandled [12,13]. Some researchers and the Costa Rican Coffee Institute (ICAFE) indicate CP management has been one of the challenged coffee by-products with the most significant volume of waste [9,14]. In addition, it accumulates for long periods, and it leads to the generation of foul odors, being a favorable environment for reproducing flies and other pests responsible for multiple diseases [15,16]. Currently, the country has a top priority: reducing GHG emissions in the coffee industry, together with a National Decarbonization Plan 2050 [17]. Hence, studying methane emissions during the composting of the coffee by-products and finding new approaches will be crucial to achieving future goals and mitigating the current challenges with coffee by-products each harvest.

Composting has been a promising technique for waste treatment in converting organic matter and agricultural residues into compost, even using minor technologies and operational expenses [18,19]. Aerobic composting involves the changes in the properties and degradation of the substrates [20]. In addition, the existence of aeration in the system gives biological products from the metabolism of the process, such as carbon dioxide, water, and [21,22] heat. During the composting process, three phases are observed in the aerobic decomposition: initial and degradation, conversion, and maturation. In addition, possess two types of microbial activity during this decomposition: thermophilic stage (45–70 °C) and mesophilic stage (15–45 °C) [21,23–26] The first stage is linked with the microbial activity of the material and is followed by a second stage, where the conversion of the organic material occurs [27]. The final stage is the maturation process, which occurs at ambient temperature and mesophilic micro-organisms play a role in finishing the product (mainly bacteria and fungi) [28]. Even if a composting technique is beneficial to the environment, GHG is present during the process, enhancing global warming [29]. The emissions will depend on the waste type and composition, key composting parameters such as C/N, temperature, moisture, pH [27,30], and the final use of the compost [31].

This study aims to develop an experimental methodology for sustainable coffee by-products for nutrient-rich compost following key composting parameters and quantify CH_4 emissions rate to obtain an emission factor for CP from open composting processes to optimize operating conditions CH_4 emissions. Furthermore, with the usage of improved management of coffee by-products, it will grand new approaches of the residue in the coffee industry. This will allow the communities and the coffee sector to receive a positive environmental impact where the aim is to reduce GHG emissions, odors, and pathogens generated. On the other hand, the farmers could make sustainable use of the compost in the future, returning soil amendment into their coffee plantations.

4.3. Materials and Methods

4.3.1. Compost Pile Construction and Mixing in the Study Area

The study was conducted in the biggest Costa Rican coffee mill in the country and located about 70 km south of the Capital San Jose, between 9°39′25.41″ N and 84°01′32.08″ W. The performance of the experiment was during the harvest and dry coffee season of 2019–2020 at an altitude of 1200–1900 m.a.s.l. [32]. The status quo of the current mill of study generates about 37,000 tons/ harvest of coffee by-products (1 harvest per year) and, 80–90% of CP is used for composting purposes. The so-called open field depositions are fields where CP is buried every harvest without composting treatment due to the lack of space for composting. Currently, in the mill, the composting process is carried out just with CP as an input material; therefore, this current technique is taken as the control (TC). Open Windrow composting trials were formed using five different percentages of two types of feedstock: CP as a coffee by-product and green waste (GW) (Table 4 - 1). CP was collected directly from the mill after the industrial de-pulping process of the coffee cherries and transported into the composting area by trucks. The collection of GW was from the surroundings of the mill and shredded for the trials and windrow formations. GW was a mixture of wood sticks, Elephant grass (*Pennisetum purpureum*), African Stargrass (*Cynodon plectostachyus*), and pruning of trees from the surroundings, including coffee plants. The feedstock was in a triangular cross-section formed (approximately 1.2 m high, 2.6 m wide, and between 15–25 m long for all the treatments).

Table 4 - 1: Overview of the treatments based on volume and amount of pulp used for each treatment for 23 windrows.

Treatment	Windrow Percentage Based on Volume	Total CP in Mg Per Treatment	Total Number of Windrows	Total of Fanegas Per Treatment **
T1	80% CP–20% GW	98.54	7	937
T2	75% CP–25% GW	36.95	3	351
T3	70% CP–30% GW	49.27	4	468
T4	60% CP–40 % GW	18.48	2	176
T5	50% CP–50% GW	9.24	1	88
TC	100% CP (Control)	105.58	6	1004

CP: coffee pulp, GW: green waste (grass clippings and weeds + structural materials), ** Fanega: typical Costa Rican coffee measure, where one Fanega corresponds to 105.2 kg of P and 253 kg of coffee fruit [34,35].

The windrows were operated without forced aeration and turned weekly using a mechanical turner (Backhus® windrow turner) for the entire process. Previous studies [10,33] have shown that the optimal turning frequency for CP during the composting process was once per week to avoid anaerobic conditions inside the windrow and methane emissions. Therefore, these considerations were also taken into account for this study.

The primary input material was CP as a coffee by-product (>50% of input). A total of 318 Mg of CP and 74 Mg of GW was used to form 23 windrows for ten weeks (Figure 4 - 1). The treatments (percentage based on volume) were decided according to the feasibility of the mill in collecting the input materials of GW. Since the interest of the mill is the implementation of the proposed treatments, this information was considered for the windrow formation. Table 4 - 1 shows that the total of windrows was different for each treatment. The study was performed during the summer season in an open space in the mill. Hence, water loss and depletion to avoid a decrease in the activity of the micro-organisms were important factors to consider. Irrigation starting from week three until week six before each turning was needed to maintain the proper moisture content in the process for T1 to T5. The irrigation was based on the WC monitored weekly and temperature profiles for all the treatments.

Figure 4 - 1: Aerial photo of the proposed treatments T1–5 (right section) and aerial photo of the current treatment at the mill TC (left section).

4.3.2. Compost Sample Analysis

Fresh Compost samples were used to quantify the gravimetric moisture content (MC), pH, bulk density (ρ_t), volatile solids (VS), and carbon to nitrogen (C/N) ratio during the process shown in Table 4 - 2. These results were analyzed in an accredited laboratory in Costa Rica for compliance with INTE ISO/IEC 17025 standards. The analysis was performed to obtain the properties of the raw materials and microbial population counts by a serial dilution technique. The procedure was made for pH and EC in water 10:25; Acidity, P, and K with Olsen Modified pH 8.5 ($NaHCO_3$ 0.5 N, EDTA 0.01M, Superfloc 127) 1:10. Acidity is determined by titration with NaOH; P by Colorimetry with Flow Injection Analyzer (FIA), and the rest of the elements by Atomic Absorption Spectrophotometry (AAS). Total %C and %N were determined with the C/N auto analyzer by dry combustion.

Once the windrow piles were formed, the MC, pH, and C/N ratio were measured weekly, and the temperature was taken manually daily by triplicate in all the windrows. The weekly samples were collected from five different locations and depths along the windrow. Thereafter, a representative sampling over the entire windrows to analyze MC and pH was obtained. All the sample analyses followed the German Quality Assurance Organization standards for Compost (BKG) [36].

Table 4 - 2: Properties for the raw material used for the composting process.

Parameters	**MC (%)**	**pH**	**CE ($mscm^{-1}$)**	**C/N**	**VS (%) DM ***	**C (%)**	**N (%)**	**P (%)**	**K (%)**	**ρ_t g/L**
SM [1]	55	6.2	2.7	59.3	77.2	47	0.8	0.08	0.7	95.4
CP [2]	82	4.9	3.9	16.1	94.76	44	2.3	0.11	3.17	432
DGW [3]	7.9	7	5.8	35	91.27	38	1.1	0.39	2.5	31.4

DM *: dry matter; SM [1]: structural material; CP [2]: coffee pulp; DGW [3]: dry grass clippings and weeds.

Water content was calculated from field moist and oven-dry (105 °C for 48–72 h) mass of compost according to the DIN EN 1304. The pH was extracted from 20 g (wet weight) of compost with 180 mL of $CaCl_2$ and assessed by potentiometric measurements. VS were performed and calculated according to the Federal Compost Quality Assurance Organization (FCQAO) and the DIN 18128. C/N ratios were analyzed using a Vario Max CN element analyzer elementar Analysensysteme GmbH® following the DIN ISO 10694. Three replicates of 10 g were inserted into a porcelain crucible into a muffle furnace at 550 °C. The samples were burned until constant weight according to the DIN 18128 and determined as sample weight loss.

After ten weeks, once the compost was finished, samples of each treatment were shipped to Germany to analyze each nutrient content and chemical parameters. A certified laboratory (PLANCO-TEC, Neu-Eichenberg) performed the mature compost analysis in Germany, following the BKG standards. The following methods were used for each parameter enlisted in Table 4-3: total nitrogen, MB BGK: 2013-05; total phosphate, potassium and magnesium DIN EN ISO 1 1885: 2009-09; soluble nitrate, ammonia, phosphate and potassium, VDLUFA I A 6.2.4.1: 2012; organic substances, DIN EN 13039: 2000-02; alkaline active ingredients MB BGK, 2006-09, soluble magnesium VDLUFA I A 6.2.4.1: 1997; Rotting degree, Methodenbuch (MB) BGK; Salinity, DIN EN 13038; Bulk Density, Plant tolerance (25% and 50% Substrate), MB BGK, 2006 and C/N ratio, QMP_BIK_C3808: 2018-09.

4.3.3. Methane Gas Sampling System

The measurements were carried out in open windrows and open field depositions. First, the focus was on whether the different windrow mixtures with coffee by-products could be comparable or compatible. Second, the differences in terms of gaseous emissions and when the volume mixture is distinct. Third, the results were compared with the mill (TC) current treatment where the composting occurs using CP as a raw material. Moreover, the determination of methane concentration was measured in the windrows and the field depositions. In this last one, the main focus occurred on determining the emissions over time (years), with the purpose to estimate how long the coffee by-products emit methane gaseous emissions when the CP is not treated.

Table 4 - 3: Final parameters of plant nutrients, soil amendment, and physical parameters of the compost treatments.

Parameters	Units	TC	T1	T2	T3	T4	T5
Plant Nutrients							
Total Nitrogen (N)	% *	1.61	1.14	1.06	1.37	1.36	1.31
Total Phosphate (P_2O_5)	% *	0.59	0.44	0.46	0.46	0.44	0.47
Total Potassium (K_2O)	% *	4.28	2.95	2.87	3.19	2.96	2.93
Total Magnesium (MgO)	% *	0.36	0.29	0.36	0.35	0.33	0.33
Nitrate $CaCl_2$-soluble (NO_3-N)	mg/L **	8	114	128	103	276	162
Ammonia $CaCl_2$-soluble (NH_4-N)	mg/L **	45	40	22	23	66	108
Phosphate $CaCl_2$-soluble (P_2O_5) 1)	mg/L **	298	133	150	122	65	51
Potassium $CaCl_2$-soluble (K_2O)	mg/L **	10,700	10,900	11,400	9750	9920	10,400
Soil Amendment							
Organic Substances	% *	60.4	43.9	37.5	47.3	45.1	40.4
Alkaline Active Ingredients (CaO)	% *	2.4	2.31	2.25	2.69	2.28	2.18
Magnesium $CaCl_2$-soluble	mg/L **	19	27	44	30	48	43
Physical Parameters							
Degree of Rotting	-	3	4	4	5	5	5
Salinity	g KCl/L **	5.97	5.14	3.96	3.76	4.53	3.68
Bulk density	g/L **	345	502	520	414	464	504
PC [1] 50% Substrate	% *	75	97	95	103	100	102
PC 25% Substrate	% *	52	82	90	87	88	95
C/N Ratio	-	22	22	21	20	19	18

PC: plant compatibility (relative yield); * Fresh mass; ** Dry Mass.

Field deposition and TC are common practices in the country; therefore, it is a quantification essential to consider. A flux chamber was placed on top of the windrow piles and inserted approximately 5 – 10 cm deep into the windrow. This was made to seal the chamber against atmospheric influences to quantify the emissions. The upper part of the flux chamber is designed with two ports (Figure 4 - 2), one inlet connected to a hose, allowing the ambient air to enter and be mixed inside the chamber, producing a constant airflow. The second port is an outlet to connect the gas analyzer in the chamber to collect the inner gas. Then, with a gas detector device, the methane concentrations are determined.

Before the gas detection, an estimation of time for the measurements was made. The estimation was considered until the emissions remained permanently constant; therefore, no variation during the measurements could occur. The measurements were conducted weekly for 15 min by quadruplicate before turning the piles in two different windrows per treatment. The methane emissions sampling took place during the first six weeks of the composting process. Measurements were halted during summer without rain events. According to the manufacturer, the sensitivity of the gas detector device was from 0 ± 1 to 60 ± 3, represented in volume percent [37]. The calculation of the methane concentrations is crucial to determine the emission rates and the emission factors.

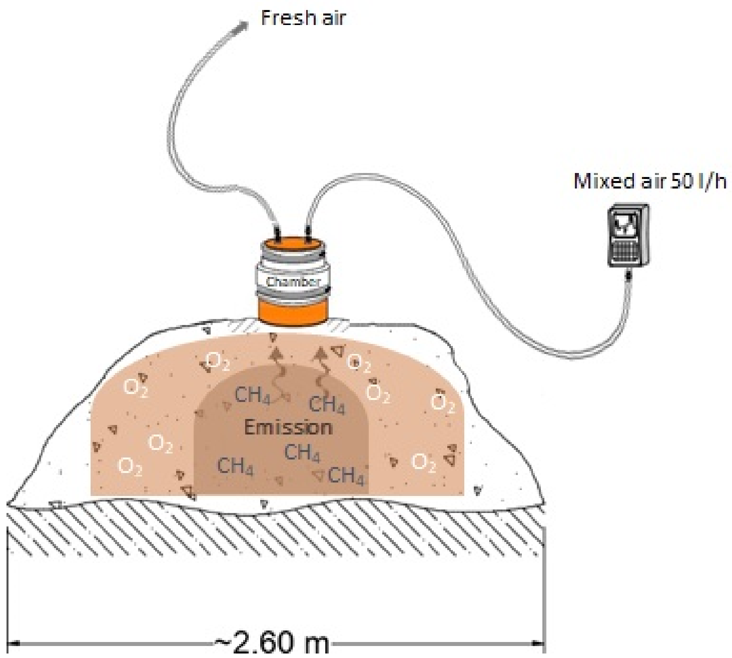

Figure 4- 2:. Diagram flow principle of gas sampling on a passive source area in a windrow.

4.3.4. Emission Rates and Emission Factors

The flow quantifies emission rates through the flux chamber related to the treatment and quality of composting. After identifying a spot, the area is encapsulated to form an aerated chamber. A defined amount of air is extracted, covering the entire area required for sampling to function the constant flow of emissions and supply of ambient air. The flux chamber allows the flux gas to diffuse, which can measure the methane concentration over time and estimate the flux gas emission [38,39] The result is the volumetric flow rate extracted per unit of time [40]. Several factors were considered for the emissions rate calculation: the sampling chamber and chamber area, the volume, and flow volume. Methane emissions rates were calculated in g × m^{-2} × h^{-1} with following the equation [10,33,41,42]:

$$q_{CH_4} = \frac{C_{CH_4} * V_{gas}}{A} \quad (1)$$

q_{CH4}—the emission rate of methane (g × m^{-2} × h^{-1}); C_{CH4}—methane concentration in (mg × m^{-3}); A—flux chamber area in (m^2); V_{gas}—gas flow volume, (L × h^{-1}).

The emission factor from a given source can be calculated as the mass ratio of gas emitted to initial fresh matter mass (kg × Mg^{-1}). However, sometimes the feedstock is reported in units of dry mass. Emission factors related to the mass of CP treated in each treatment and calculated as:

$$EF_{CH_4} = \frac{qCH_4 \times t_{treat} \times A_{treat}}{m_{treat}} \quad (2)$$

EF_{CH4}: the emission factor of methane related to the mass of CP treated (g × kg^{-1}); q_{CH4}: the emission rate of methane (g × m^{-2} × h^{-1}); t_{treat}: duration (time) of treatment (h); A_{treat}: area of treatment (surface area of the emission) (m^2); m_{treat}: the mass of treated material (mass of CP at the pile) (kg).

4.3.5. Statistical Analysis

A one-way analysis of variance (ANOVA) test was carried out to investigate the correlations between emissions rates and the period in weeks of composting in the windrows. A significance level of $p \leq 8.9 \times 10^{-8}$ for the composting treatments was used for all mean values. In addition, the Tukey HSD test (α = 0.05) was used to assess significant differences between treatment means at a 5% probability level.

4.4 Results and Discussions

4.4.1 Environmental Conditions: Temperature, Moisture, and pH

At first, all the material is nearly identical, but heat is generated by increasing the temperature as the micro-organisms grow [43]. One of the indicators of microbial activity is the increase in temperature inside the windrow, where the temperature has traditionally been considered a fundamental variable in the control of composting [44]. Figure 4 - 3 shows the temperature profiles for all the windrows. TA refers to the ambient temperature. Additionally, during those 70 days of the composting process, the windrows experienced no rain events. Figure 4-3 shows a typical development for composting processes containing self-heating, cooling, and stabilization phases. The turning of the material caused low peaks, reflected in the graphs. Sanitation or hygiene is crucial to destroy pathogenic micro-organisms, seeds, and plant components for future sprouting [30,45]. The sanitation process in a windrow should experience at least 14 days of high temperatures (above 55 °C) to enhance the sanitation process [24,46]. The sanitation process was achieved in the temperatures profile for all the treatments maintaining the high temperature at least for the recommended period. The addition of green waste produced different behavior regarding temperature profiles and thermophilic stages within the windrows.

Comparing the temperature increased in the treatments, T1 accelerated the temperature profile by 38%, T2, T3, and T5 by 72%, and T4 is the most notorious by 83% compared with TC. During the maturation phase, the temperature in the windrows began to decrease until it reached temperatures of 35 °C among the windrows. TC experienced the increase in temperature and the thermophilic stage after 29 days, T1 after 18 days, T2, T3, and T5 after eight days, and T4 after five days of the composting process. The addition of green waste into the windrow has accelerated the degradation, microbial activity, and temperature profile within the windrows. T1 experienced the most extended period for reaching the thermophilic stage, attributed to the CP percentage in the piles (80% P). The observed variation in periods of high temperature could be attributed to the variation in the percentages of GW in each treatment [47]. For example, the behavior of T1 is the closest to the profile of the control TC. This is attributed toT1 containing the highest amount of CP in the composting treatment.

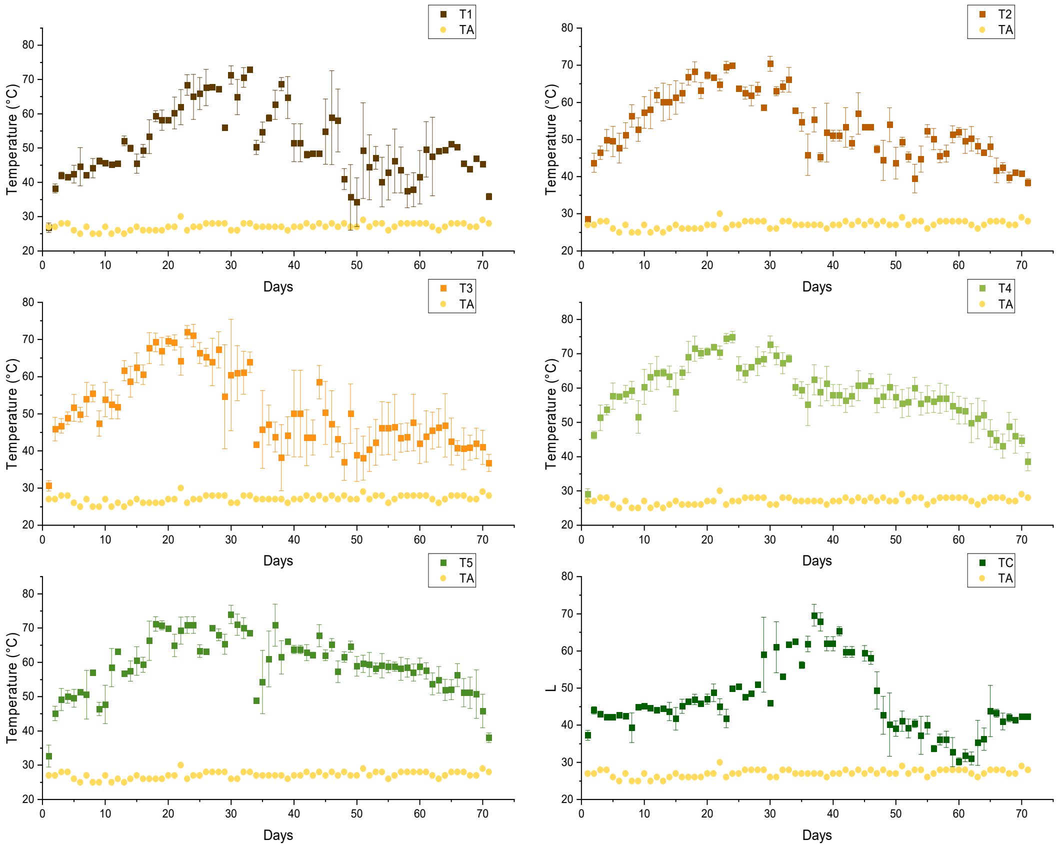

Figure 4 - 3: Temperature profiles in all the types of windrows. TA: ambient temperature. Bars represent the standard error of the mean (n = 4).

During aerobic windrow systems, moisture and aeration are important parameters to consider to enhance the biological activity inside the windrow [48]. It is recommended during the composting process to maintain a moisture content between 50 – 60% for favorable results [23] and the avoidance that water fully occupies the pores of the composting mass [44]. This parameter is essential for CH_4 emissions control during composting and affects degradation and end-product features [5]. Furthermore, evaporation is linked to the lack of porosity and aeration in the system and the relationship between air to water ratio [30,49].

Microbial activity, including bacteria, fungi, and yeast, depends on temperature and moisture content [27]. The aim of this study was not the microbial counts weekly during the composting process. Instead, a general overview of the microbial activity was considered important to control the microbes in at least two treatments to ensure that the activity is higher than the control TC with the proposed technique. Quantitative analysis was based on colony counts and subsequent calculation of colony-forming units per gram (CFU/g) to estimate the viable number of bacteria, fungal cells in the samples during the third week of composting process for TC, T1, and T3 (Figure 4 - 4).

Results show that the microbial activity is higher for T1 and T5 than for TC. During the third week of composting, T1 and T2 reached thermophilic temperatures, and the amount of yeast from Figure 4 - 4 compared to TC can be linked to this event. Some studies show that higher temperatures for T1 and T5 induced an earlier microbial activity [50]. For this case, Figure 4-4 shows that temperature during the third week was below 50 °C, whereas T1 and T5 had temperatures above 50 °C. Low moisture content (below 40%) limits microbial activity [21].
On the other hand, very high moisture enhance anaerobic conditions because the pore spaces are filled with water rather than air [51]. Among those variables, the moisture content is considered one of the key parameters affecting the biodegradation process. Furthermore, some studies have suggested an important influence on microbial activity linked with MC than with the temperature [50]. In addition, the number of input materials can change the microbial communities, where T5 possesses the highest amount of green waste material among the piles. This ensures that adding materials to P improves the activity of the micro-organisms, enhancing the composting process.

Each windrow treatment varied regarding the response to water consumption and evaporation. The monitoring was important during the composting process to obtain sufficient conditions for T1–T5 and compare with the current treatment at mill TC. Over ten weeks, moisture content was measured among the different windrows represented in Figure 4-5. During the first week, all the treatments showed a high moisture content due to the high levels of moisture that CP possesses by itself (Table 4 - 2). After the second week, all the windrows except TC reached the recommended moisture content levels for the composting process. Thus, TC has reached the levels recommended after six weeks of the process. In TC occurred no variation during four weeks of pile age. The high value is attributed to the high MC of the coffee by-product. T1–T5 had rapid absorption with the percentages of the mixture of GW and CP. It was observed that the highest amount GW added in the windrow, the fastest was the reduction of the MC in the system after the second week of the composting process. Additionally, pH directly influences composting due to its action on the dynamics of microbial processes [52]. For this study, pH in all windrows rapidly increases within three weeks of all the treatments (Figure 4 - 5), showing a tendency. Subsequently, an alkaline state was seen for the rest of the composting process. Some authors have seen a link between the loss of organic acids and the generation of ammonia from the decomposition of proteins and this alkaline state [10,53 – 55]. In all the windrows, at the end of the process, the pH of the treatments was basic (8.8 – 9.8), indicating maturity since lower pH values would indicate anaerobic processes [56].

Some studies have shown that the alkalinity can be attributed to the high potassium (K) content of the input materials [57], such as using the CP as the primary raw input material for the process (Table 4 - 2) [58]. This observation was consistent with the results of this study, showing that the highest pH values were obtained in TC for the last week of the process. The windrows T1 - T5 show results as a mature compost, whereas TC indicates an immaturity. The turning and aeration are also important to factor during the pH behavior in the window systems. Having good aeration and oxygen concentration is obtained low concentrations of organic acids enhancing the decomposition of these acids and giving a faster rise in the pH [59].

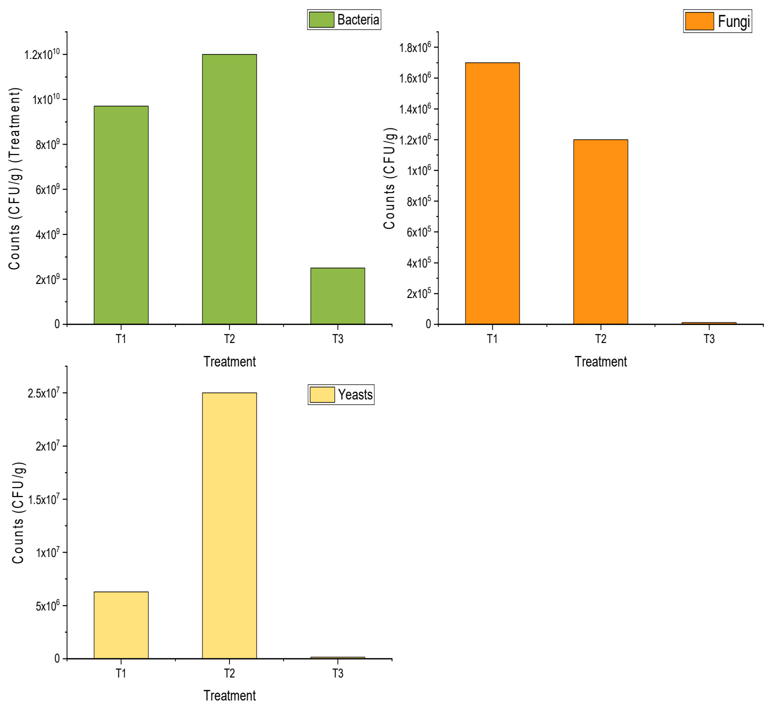

Figure 4 - 4: Comparison of mean colony-forming unit (CFU/g) for samples T1, T5, and TC during the third week of the composting process.

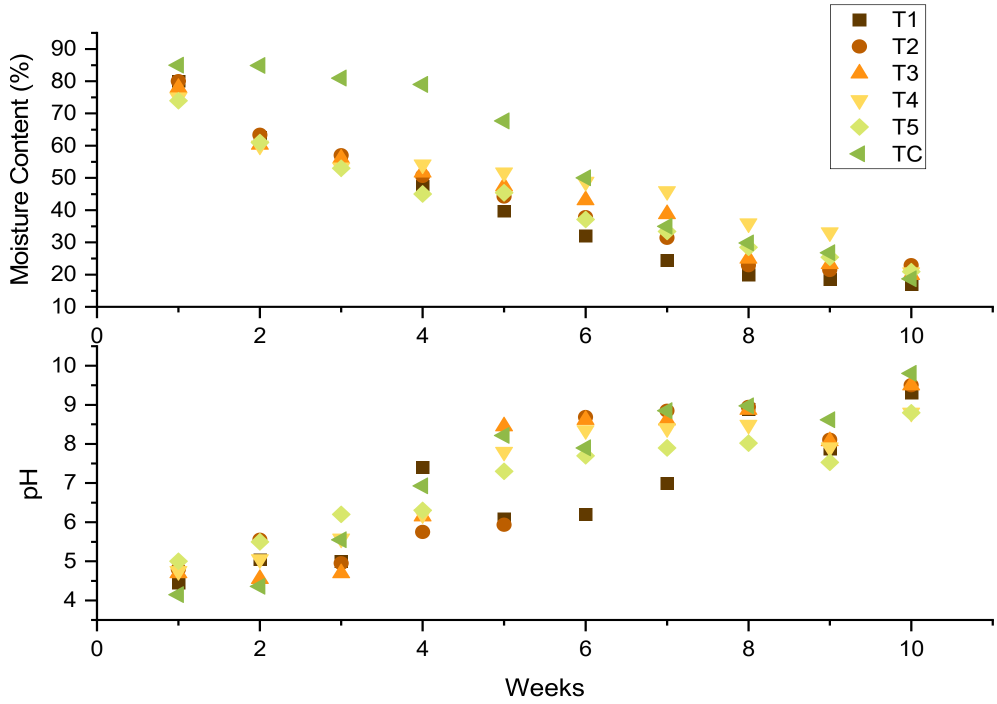

Figure 4 - 5: Moisture content and pH profiles in all the types of windrows throughout CP composting. Values are the means (n = 3).

Once the ten-week composting period was achieved, and the low temperatures remained constant, the samples were shipped to Germany. They were delivered to an accredited testing laboratory for the BGK to analyze plant nutrients, soil amendment, and final physical parameters for the windrows. These results are summarized in Table 4-3. The elements include nitrogen (N), phosphorous (P), and K, which are fundamental macronutrients for microbial growth. [60]. The total of nutrients is essential since it can vary and allows the mill to determine an appropriate end-use for the compost. N, P, and K are the macronutrients that make the biggest uptake [61]. N is assimilated by the plants in the forms of nitrate (NO_3^-) and ammonium (NH_4^+), P in forms of orthophosphate ($H_2PO_4^-$), and K in the forms of potassium oxide (K_2O) [62]. Nevertheless, attention must be focused on the availability of these nutrients, which is known as a limiting growth and uptake factor [62]. In this case, T4 presents high levels of N and NO_3^-, which the plant can assimilate immediately. It also contains high NH_4^+ levels, which need a process in the soil for the plant to absorb [60], giving a good combination of NO_3^- and NH_4^+. Finally, it contains the highest value of soluble magnesium (Mg), meaning practical use in crops in the future since the soils of coffee production possess a common Mg deficiency

[63]. Furthermore, Mg gives color to the plant as it is the central atom of the chlorophyll molecule [64]. To summarize, T4 shows the best performance in the nutrient content, and it is suggested for future usage in the coffee plantations as an additional amendment. It contains high N, NO_3^-, and Mg, which could be used as a plant stimulant in some phenological parts of the crop.

High salt levels can be unfavorable for seeds and plants when compost is for a nursery medium [65].TC showed the lowest plant compatibility test associated with the degree of rotting and the salt levels; meanwhile, the rest of the treatments proposed showed a >95% for plant compatibility and low salt content. Bulk density among the proposed treatments fulfills the BKG limit values (between 400–900 g/L); meanwhile, the control obtained the lowest bulk density value. This could carry consequences in compost application since the material can suffer high pore space and common water retention values, causing difficulties in future compost applications. The lowest C/N ratio was obtained in T5, whereas TC possesses the highest value. Even though CP owns low C/N, this increase is linked to the mineralization of organic N, promoting the ammonia emissions, leading to a high N loss when the initial C:N is low. [66].

On the other hand, the results show high total K values. They are attributed, as previously mentioned, to the high potassium content of the CP since it contains more nitrogen and K than other common finished materials as compost [9]. Regarding the organic substances, BKG recommends values higher of 30% based on dry mass for finished compost. Higher levels indicate that the compost is not finished, as is the case of TC. The rotting degree or self-heating test is considered an important parameter indicating heat in the windrow, showing signs of immaturity. The five categories of the interpretation scale are grouped, often made by professionals and European agencies, into three main classes. The lowest grade (I) is called "fresh compost", the two intermediate grades (II,III) are called "active compost," and the top two grades (IV,V) are called "finished compost" [36]. For all the treatments, the grade was IV and V except for the control.

4.2. Methane Gas Emissions

The CH_4 is influenced by different factors such as temperature, moisture, and pH directly [67]. When the aeration is not proper and the moisture content increases in the windrow, this can result in high CH_4 emissions affecting the oxygen restrictions in the microbiological metabolism in the windrow [5,68,69]. Methane emissions rates shown in Figure 4-6A were measured during the first six weeks of the composting process and compared if the addition of GW influences their emissions in the windrows. The highest value is TC with 38 g × m^{-2} × h^{-1} in the first week of composting. Comparing Figure 4-5 of MC and Figure 4-6, the first week of composting process possesses the highest value for moisture content among the study. Thus, the production of CH_4 is also increased exponentially with the moisture level, allowing the formation of undesirables anaerobic zones enhancing the methanogenesis and anaerobic metabolism in the windrow [30,33]. Even if the composting treatment is under aerobic conditions, the diversity of the input materials, moisture content, temperature, biological microbial activity, and redox requirements could be developed in the window [2].

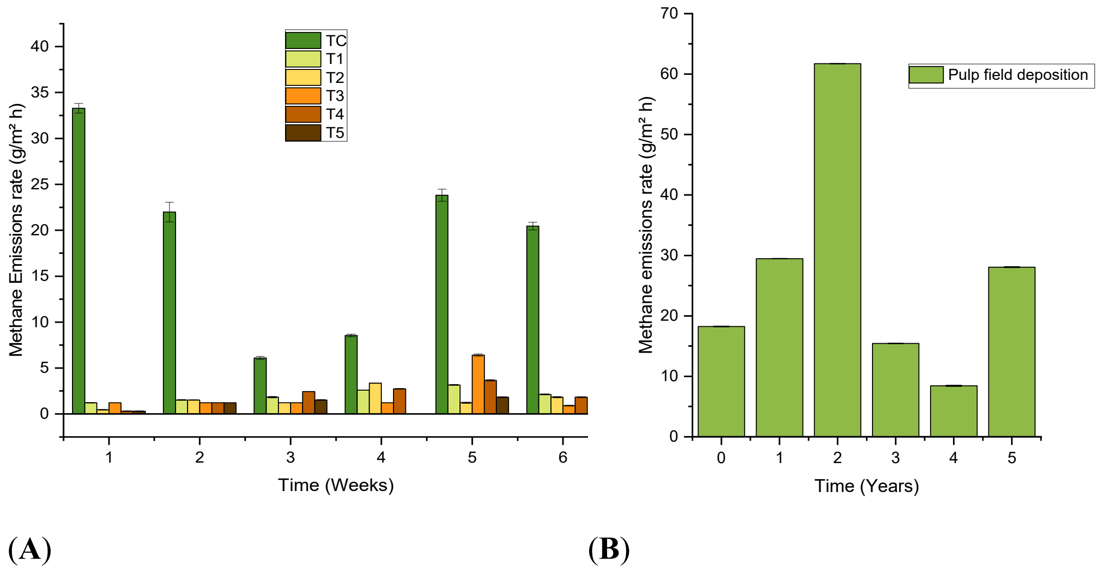

Figure 4 - 6: (A) Methane emissions rate for all the treatments using coffee pulp for composting and (B) methane emissions rate in field deposition. Bars represent the standard error of the mean (n = 4).

In this study, the reduction of CH_4 during composting is accomplished if additional material is used, such as GW. The weekly highest values among the treatments were found for T1 and T2 with 3.1 g × m^{-2} × h^{-1} and 3.3 g × m^{-2} × h^{-1}, respectively. Each value was found during the fourth week and for T3, T4, T5 with 6.4 g × m^{-2} × h^{-1}, 3.6 g × m^{-2} × h^{-1}, and 1.8 g × m^{-2} × h^{-1}, respectively in the fifth week. Emissions formation increases faster when temperatures are over 65 °C [3]. Furthermore, a correlation between the temperature profiles and the emissions peaks is shown since the highest peaks of temperatures and emissions were found for the windrows during the same weeks of the composting process.

The presence of low pH, which illustrates the presence latency of organic acids, and the present of also CH_4 emissions, indicates that anaerobic conditions have been since the initial formation of the windrow pile [68]. The reduction of total emissions CH_4 was between 89–95% compared to the control treatment, which shows the difference of aeration and proper management within the treatments compared to the control. Researchers recommend that increasing the oxygen level available in the system is necessary during the first week [3]. In the fifth week, methane emissions were higher than in the first week for T1–T5. This could be attributed to the moisture suppressing the airflow since the material at that week is more compact. The pores in the feedstock are filled with water, favoring the formation of anaerobic conditions and methane emissions [31]. The emissions in the fifth week were the highest among the treatment compared to the control TC. The reduction of emissions with GW is added in the window is seen. In other studies, it has been found that CH_4 emissions are present during the initial stage of the thermophilic phase since there is an oxygen solubility reduction, enhancing anaerobic zones in the windrow [70]. During CH_4 emission exists other microbial factors affecting the gas transport and gas diffusion, including the presence of methanotrophic bacteria (these bacteria are colonizing the area nearby anaerobic zones being able to oxidize up to 98% of the CH_4 formed in the windrow) [71].

A previous study [10] shows the magnitude of the CH_4 emissions in open field depositions when the CP is not composted or pre-treated before field deposition, generating serious environmental concerns. Figure 4-6B shows the behavior of the methane emissions over the years when the CP is buried for a lifetime. The highest emission was in the second year with $53.7\ g \times m^{-2} \times h^{-1}$. Equivalent emissions are seen in the first and the fifth year of field deposition with 25.6 and $24.4\ g \times m^{-2} \times h^{-1}$. These results imply that the material is not degraded over time, producing continuous emissions of great magnitude when not treated correctly. This behavior of high CH_4 emissions over this period is due to the properties of the CP. When it is buried with high moisture content, high material density, and a lack of aeration, anaerobic zones are created, enhancing the methane emissions.

Given this problem and its emissions, the mill aims for successive harvests to avoid this practice. For example, during the 2019–2020 harvest, open field depositions were made with about 630 Mg (6000 fanegas). In previous years, a minimum of 1500 Mg of CP was transported in the fields. It is clear that the depositions are a risk and a focus of emissions since they are large spaces of at least 925 m^2 of surface area; therefore, the high levels of emissions over the years can be attributed to the surface area, amount of material, and the management in that area.

For the estimation of EF among all the treatments, it is shown in two different options. Firstly, a calculation of EF regarding the amount of CP added in each treatment. It is crucial to establish since there is no EF associated directly with CP in the literature, where the results show that the more CP added into the system, the higher EF is obtained. After this, an EF calculation was input to represent the treatments better and was compared with literature regarding green waste from some regulations in composting plants.

The government is currently developing a new national composting plan accomplishing the strategic guidelines of the National Decarbonization Plan 2050. The inventories of GHGs in Costa Rica regarding waste management are made by the National Meteorological Institute (IMN for its abbreviation in Spanish). Therefore, the results in this research are compared with the National Inventory's values; nevertheless, it is necessary to be analyzed. These inventories are for municipal solid waste; therefore, these results cannot be thoroughly compared since the country does not explicitly relate to agricultural waste. On the other hand, there is no emission factor directly linked to CP; a comparison in the literature shows 4 g CH_4/kg solid waste [72], 4 g CH_4/kg waste treated [73], 2.2 g CH_4/Mg GW FM [5], 4.7 and 7.6 g CH_4/kg GW [74].

The emissions factors shown in Table 4 - 4 show the decrease of emissions comparing TC with the rest of the treatments. The utmost emission values found were in T3 and T4 with 14 g CH_4/kg CP. The closest value compared to the literature is T5. One of the reasons could be the amount of GW added since it had the most significant amount of material in a pile. Compared with the literature values of biological treatments, these results present elevated values. However, with the proposed methodology for all the five treatments, these values are approaching the values recommended by the literature for composting. For the open field depositions, even if there is no management involved, the emissions factors represented the highest values among all the treatments, including the current treatment of the mill.

Table 4 - 4: Emissions factors from all the treatments proposed**.**

Treatment	EF (g CH_4/kg CP)	EF (g CH_4/kg input)	SD*
T1	43.9	35.1	0.23
T2	14.4	10.8	0.17
T3	20	14	0.23
T4	23.4	14	0.24
T5	11.6	5.8	0.14
TC	129	129	2.96

SD*: Standard Deviation of the mean values (n=4).

4.5. Conclusions

The study achieved the development of an experimental methodology using coffee by-products and GW. An improvement in the key parameters of composting was observed, such as temperature, pH, and WC profiles, when coffee by-products were mixed with GW for composting treatment. Therefore, waste valorization within the process is concluded together with the reduction of methane emissions. The proposed treatments experienced fewer methane emissions rates than the control; hence, implementing this technique suggests a good practice in the future for the coffee sector and the mill in Costa Rica. Results show that T2–T5 are strongly recommended treatments involving methane emissions, physical parameters during the process, plant nutrient content, and finished compost classified (Grade IV and V) following the BKG standards. Overall, this study promotes a better understanding of the performance of CP when the material is composted and their methane emissions during the process. This approach might be necessary for the future to guide a national mitigation plan in the agricultural and coffee sector of the country. In addition, it will be a helpful tool for the future calculations of the global emissions using a technology already studied in another place or another treatment plant. Suppose it is considered the agronomic and environmental aspects in an integrated manner. It is recommended to investigate further the benefits of using the compost and the relationship between GHG emitted during the process. The compost utilization can also compensate for this reduction in the long term in the coffee plantations. Continuous but robust research is suggested to develop emissions and factors that adequately cover national conditions to establish new inventories, especially for the coffee sector, including coffee by-products and management.

Author Contributions: conceptualization: M.S.M.R., M.R.; methodology: M.R., M.S.M.R., and M.K.; validation: M.R., M.K., and M.S.M.R.; formal analysis: M.S.M.R., M.R.; investigation: M.S.M.R.; M.R., and M.K.; data curation: M.S.M.R., M.R.; writing—original draft preparation: M.S.M.R., M.R.; supervision: M.K., M.K., and M.S.M.R.; project administration: M.R., M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been financed by the Coffee Mill Coopetarrazú R.L in Costa Rica.

Acknowledgments: We gladly thank the personnel, laboratory assistances, students, and colleagues of the Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) at the University of Stuttgart.

Conflicts of interest: The authors declare no conflict of interest.

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5. Publication III: Nitrous Oxide Emission Fluxes in Coffee Plantations during Fertilization: A Case Study in Costa Rica

The content of this section has been published in the scientific journal *Atmosphere*: San Martin Ruiz, M.; Reiser, M.; Kranert, M. Nitrous Oxide Emission Fluxes in Coffee Plantations during Fertilization: A Case Study in Costa Rica. *Atmosphere* **2021**, *12*, 1656. https://doi.org/10.3390/atmos12121656

5.1 Abstract

The main source of N_2O emissions is agriculture, and coffee monocultures have become an important part of these emissions. The demand for coffee has increased in the last five decades. Thus, its production in agricultural fields and the excess of fertilizers have increased. This study quantified N_2O emissions from different dose applications and types of nitrogen fertilizer in a region of major coffee production in Costa Rica. A specific methodology to measure N_2O fluxes from coffee plants was developed using Fourier-transform infrared spectroscopy (FTIR). Measurements were performed in a botanical garden in Germany and plots in Costa Rica, analyzing the behavior of a fertilizer in two varieties of coffee (Catuai and Geisha), and in a field experiment, testing two types of fertilizers (chemical (F1) and physical mixture (F2)) and compost (SA). As a result, the additions of synthetic fertilizer increased the N_2O fluxes. F2 showed higher emissions than F1 by up to 90% in the field experiment, and an increase in general emissions occurred after a rain event in the coffee plantation. The weak levels of N_2O emissions were caused by a rainfall deficit, maintaining low water content in the soil. Robust research is suggested for the inventories.

Keywords: nitrous oxide; emissions fluxes; coffee

5.2. Introduction

One of the biggest anthropogenic greenhouse gas (GHG) sources and sinks for nitrous oxide (N_2O) contributing to climate change, is agriculture [1,2]. N_2O is 265 times better at trapping heat than carbon dioxide, which means that even small emissions of N_2O affect the climate [3]. Fertilizers are sources that enhance plant growth, and they can be natural or synthetic, providing key macronutrients such as nitrogen (N) that are important for leaf growth [4,5]. Studies indicate that N_2O emission could be correlated with synthetic nitrogen fertilizer (SNF) application rates in linear or nonlinear relationships in agroecosystems [6,7]. Studies imply that indirect sources come from nitrogen leaching and runoff from agricultural soils, [8]. Volatilization and deposition of ammonia from fertilizers is applied to crops [9]. Direct source is SNF, which once applied, is used by the bacteria living in the soil to produce the necessary energy required to live and grow [10]. Due to the excess supply of fertilizers, the production of N_2O, in agricultural fields provokes intermediate emissions [11]. When the fertilizer is combined with favorable soil conditions for denitrification, large amounts of N_2O can be produced and emitted to the atmosphere [12]. The main sources of N_2O production are nitrification and denitrification, and both can occur simultaneously [13]. The production is linked directly to the composition of soils and environmental conditions such as carbon sources, redox potential, nitrate (NO_3^-), oxygen (O_2), nitrite (NO_2^-), sulfur (S_2^-), and pH [14]. During nitrification, ammonium is converted to nitrite [15]. Denitrification occurs when nitrites are reduced to N_2O and inert N_2 under anaerobic conditions [7,10]. Several microorganisms and conditions act within the process, which are linked directly with the compostition of the soils [16]. The variety of the soils delineates the behaviours and periods of the processes mentioned for the production of N_2O, but it is important to measure the N content to diagnose the sources of the emissions. Then, the N_2O can be produced during the next stages, shown in Figure 5 - 1 [16,17,18].

The main N_2O emissions hotspots in Costa Rica come from fertilizer production. The direct and indirect soil N_2O emissions come from organic fertilizer (such as coffee pulp) [19]. According to the Coffee Institute of Costa Rica (ICAFE), technology for coffee production has become intensive instead of extensive within the last 20 years, generating more productivity for the units harvested. The techniques include using fertilizers to bring nutrients to a healthy level, causing an increase in emissions during coffee production, leading to impacts such as global warming at the farm level [20,21].

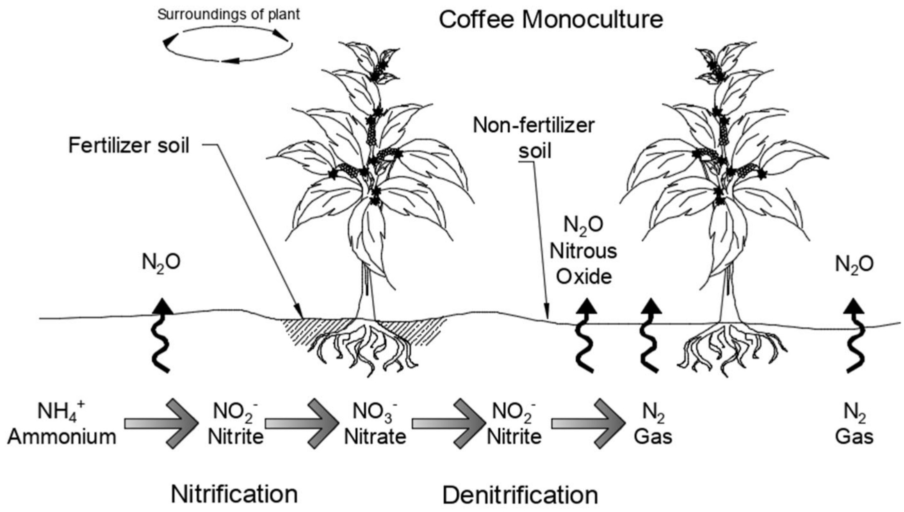

Figure 5 - 1: Nitrogen transformation within the soil profile and N_2O emissions in a coffee monoculture**.**

Therefore, this study aimed, at first, to develop a measurement strategy for N_2O emissions in a botanical garden in Germany, in order to apply this methodology to a coffee plantation. Subsequently, we performed an evaluation of the N_2O emission fluxes from the soil from a coffee plantation in the Central Valley of Costa Rica. After that, field experiments were conducted in Costa Rica, comparing emissions from two varieties of coffee plants, and a field experiment trial, using SNF and compost application. Finally, the quantification of N_2O emission fluxes and their impact on the carbon footprint of the fertilizers for the sector in Costa Rica was achieved.

5.3. Materials and Methods

5.3.1 Site Description and Fertilization

The measurements were established in Tarrazú canton, in the Los Santos zone, which is located about 70 km south of the Costa Rican Capital, San Jose, between 9°39′25.41″ N and 84°01′32.08″ W. The experiment was conducted during the coffee production season of 2018–2021 at an altitude of 1200–1900 m.a.s.l., during the dry season [22]. The total area of coffee plantations along the mountain range is more than 90,000 hectares and between 600–1600 m.a.s.l. [23], and the age of the coffee plants ranges between 15 – 20 years old. In the Los Santos zone, the annual average wind speed ranged between 0.5 km/h – 2.4 km/h; the annual average temperature was between 19°C–24°C. The annual average precipitation for the summer season was between 0–100 mm/month and for the rainy season was between 250–418 mm/month, and the annual average of relative humidity was between 79–85% [24]. The soil of this zone in Costa Rica is acidic by nature (around pH 5.0), which also tends to increase due to acidifying nitrogen such as ammonium nitrate and urea [25]. Specifically in this zone, the soils can be classified in the order of Ultisols (red clay soils), suborder of Humults, large group Palehumults, and subgroup Aquic Palehumults [26,27]. The weather is biseasonal and defined by how much rain falls during a particular period. Therefore, the year can be split into two periods in that zone, with a dry season (December–April) and a rainy season (May–November), with an average temperature between 26°C and 32°C for the dry season and 17.5°C and 20°C for the rainy season [28]. For this study, soil analysis was conducted in the area where the gas sampling was performed. Table 5-1 shows the main parameters analyzed. The soil samples were taken from five random subsamples among the plots. Subsequently, the five subsamples were mixed using a quartering technique. The samples were delivered to the laboratory for analysis and the results were given as mean values from the report analysis, obtaining the results shown in Table 5-1. The procedure was designed for pH and electrical conductivity (EC) in water 10:25; phosphorus (P), and potassium (K) with Olsen-modified pH 8.5 ($NaHCO_3$ 0.5 N, EDTA 0.01M, Superfloc 127) 1:10. Acidity was determined by titration with NaOH (P) by colorimetry with a flow injection analyzer (FIA), and the rest of the elements by atomic absorption spectrophotometry (AAS). Total %C and %N were determined with the C/N autoanalyzer by dry combustion. CEC (effective cation exchange capacity) was calculated as the sum of the acidity + Ca + Mg + K. The AS (percentage of acidity saturation) was calculated as (acidity/CICE) x 100.

Traditionally, the fertilization of coffee plantations combines the application of multi-nutrient fertilizers (NPK^+, Mg^{+2} and B^{+3}) known as “complete formulas.” Nitrogen is the main component, whose application is carried out at the end of the rainy period receiving the name of “extra nitrogen”, controlled by the agronomists and the farmers of the coffee plantations. In the study area, ammonium nitrate was predominant, ranging from 53% of N fertilizers, and in the country, the majority (94%) is distributed between ammonium nitrate with 56% and dolomitic ammonium nitrate with 38% [29]. Three fertilization events were carried out during the annual cycle of the crop. The normal fertilization process in the zone was performed in May, August, and October. At the farms in Costa Rica, there are currently four types of doses of nitrogen fertilizer that have been applied in the coffee crops [29]. The number of doses applied and the fertilization period listed below in Table 5 - 2.

The fertilization is made under a band application, and it was performed according to the normal cultivation season of fertilizer application. ICAFE recommends, in addition to chemical and physical mixtures of fertilization, the application of organic fertilizer at a dose of 2 kg/plant. Once the coffee plant has reached two years old and starts its production cycle, it is recommended for all regions in the country. Complete formulas should not contain less than 15% N.

Table 5 - 1: Soil analysis for coffee plantations.

Parameters	Units	A*	B**	C***
pH	H_2O	5.5	4.9	5.0
Acidity		0.14	1.38	0.50
Ca		8.13	4.96	6.79
Mg	cmol(+)/L	3.04	1.33	2.75
K		2.27	0.56	1.85
CEC		13.58	8.23	11.89
AS	%	1	17	4
P		12	1	4
Zn		7.4	3.2	6.3
Cu	mg/L	8	12	8
Fe		312	312	242
Mn		19	39	85
EC	mS/cm	0.4	0.2	0.4
C	%	3.63	2.61	2.93
N		0.35	0.23	0.27
C/N	Ratio	10.4	11.3	10.9

A*: soil control area; B**: soil control area without pesticides; C***: soil with 40% fewer N-based fertilizers and compost application.

5.3.2. Experimental Design and Sampling

The experimental design was created in a nursery and Moorish greenhouse in a botanical garden (zoological–botanical garden Wilhelma, 48°48′14.84″ N and 9°12′29.1″ E) in Stuttgart, Germany, to obtain a methodology for N_2O measurements to apply to coffee plantations in Costa Rica, and the first ranges of N_2O concentration over the surface of the soil of coffee plants (Figure 5 – 2 A,B). The average sizes of the coffee plants in the nursery greenhouse were approximately ~15 cm in the first 1–3 months (small size) and ~60 to 70 cm in 4 to 6 months (medium sized) in pots. The adults plants were located in the Moorish greenhouse planted in the soil. Therefore, there was no competition between adults and young plants or any physical contrains since the plants were divived by the young plants in the nursery greenhouse and the adults in the Moorish greenhouse. The fast growth is caused by the fertilizer shown in Table 5-2, that is enriched with N, K, and P. The reason for this is to reach a significant quantity of sunlight. However, there was no belowground competition between different plants or resources because every coffee plant has its own pot and receives specific irrigation with fertilizer in each one in the nursery greenhouse for the small and medium-sized plants

The N_2O fluxes were determined by an open, dynamic hood measurement method. Here, the ambient air was sucked with a constant flow through the hood. The difference in gas concentration of N_2O in the ambient air (background concentration) and the off-gas stream from the hood (equilibrium concentration) were continuously measured using a portable gas analyzer (Fourier-transform infrared (FTIR)). Before the open hood is placed, no difference exists between the hood off-gas and the atmosphere. After placing the hood, an air exchange begins, which reaches equilibrium when the amount of N_2O flowing out of the hood equals the flux of N_2O emitted from the ground. From this point on, the N_2O concentration difference between the hood and the environment and the flow rate divided by the soil area covered by the chamber equals the soil emission rate

The N_2O concentrations were taken using methods in [30–35]. The chamber was made of a polyvinylchloride (PVC) material with a cylindrical shape, enhancing a better mixing of the enclosed air, fitted with a vent to avoid pressure changes during the measurements. This device identifes up to 50 gas compounds from samples that are under different environmental conditions, and possesses a detection limit of < 3 times spectral baseline noise [36]. Based on Beer’s law, the maximum value in the peak of the curve is directly proportional to the concentration of any compound [36]. The main principle of FTIR is to identify the radiation absorbed in molecules with its characteristic frequency (wavelengths). Furthermore, each molecule has its own combination, making it possible to identify any component as a fingerprint (molecule distribution) for almost any kind of gas [36].

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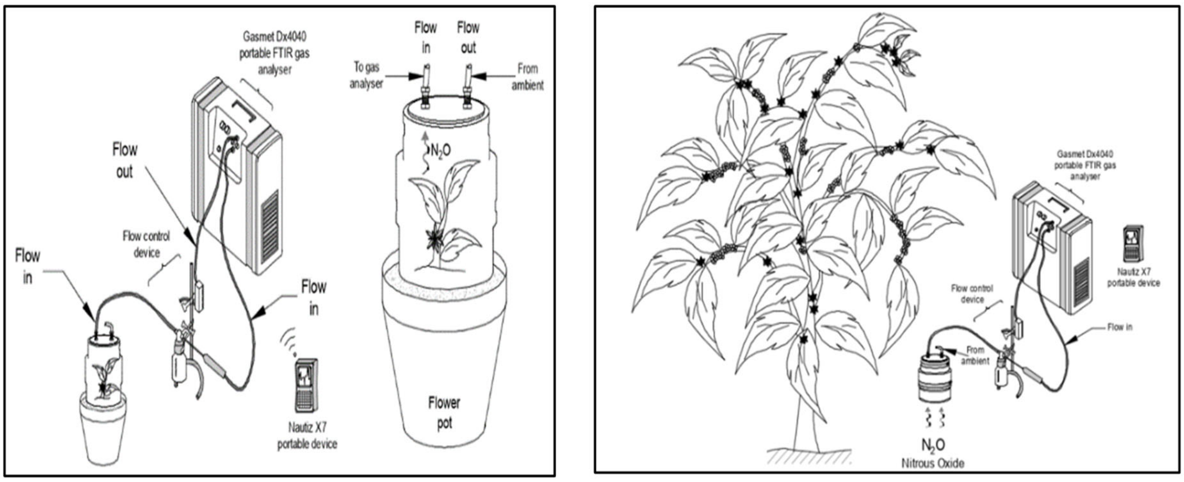
Table 5 - 2: Fertilization, doses, and types of fertilizers considered.

Fertilization Period Costa Rica 2019–2020				
22 June 2019	28 August 2019	27 October 2019	31 May 2020	20 August 2020
Formula/Amount per plant				
17(N)-6(P_2O_5)-18(K_2O)-5(MgO)-0.2(B)-0.1(Z)-1.6(S)	17(N)-6(P_2O_5)-18(K_2O)-5(MgO)-0.2(B)-0,1(Z)-1.6(S)	20(N)-8(MgO)-11(Ca)	18(N)-5-(P_2O_5)-18(K_2O)-0.2(B)-7.3(S)	17(N)-6(P_2O_5)-18 (K_2O)-5(Mg)-0.2(B)-0.1(Z)-1.6(S)
Amount added: 90 g/plant				

Percentage of Fertilizer Used in Nursery Greenhouse in the Botanical Garden				
Component	Week 5 July 2019 vol in %	Week 9 July 2019 vol in %	Volume Mixture for Small-Sized Plant (mL)	Volume Mixture for Medium-Sized Plant (mL)
Nitrogen (N)	20	15		
Potassium (K_2O)	20	20	100	200
Phosphorus (P_2O_5)	20	25		

Fertilizer Assay—04.2021 in Costa Rica		
Chemical Fertilizer (F1)	**Physical Mixture Fertilizer (F2)**	**Soil Amendment (SA)—Compost Coffee By-products**
17 (N)-6(P_2O_5)-18(K_2O)-5(Mg)-0.2(B)-0.1(Z)-1.6(S)	18(N)-5(P_2O_5)-15(K_2O)-7.3(S)-6(MgO)-0.2(B)	1.37(N)-0.46(P_2O_5)-3.19(K_2O)-0.35(MgO)
Amount added: 90 g/plant		Amount added: 2 kg/plant

The N_2O concentrations were obtained per minute directly through the FTIR during one hour of measurements, and one chamber was placed for each measurement in a coffee plant. As mentioned above, the concentration in the chamber depends on concentrations and flow rates of the incoming and outgoing airflows (between the soil air space, the chamber, and the ambient air). Therefore, emission rates were determined and calculated until the concentration reached an equilibrium in the chamber.



(A) (B)

Figure 5 - 2: (A): Experimental setup in the botanical garden for small–medium-sized plants. (B): Measurements in coffee plantations and botanical garden for adult plants using an open dynamic chamber.

After that, the first measurements in Costa Rica took place, quantifying the amount of N_2O fluxes depending on the fertilization period of each measurement. Then, the punctual measurements were made at different periods during day time (between 7:00–15:00) over the years, to understand the behavior of the N_2O fluxes depending on the season and the amount of fertilizer normally applied in the coffee plantation.

Parallel to this, daily monitoring and measurements were performed for 30 days in a plot in Costa Rica to obtain a semicontinuous flux when the fertilizer was added. Finally, the fertilizer was applied manually to the base of the coffee plant (band fertilization), following the process at the coffee farms (Table 5 - 2). In this case, two types of fertilizer were added in two different coffee plants, 2 kg of compost in one plant coming from the coffee by-products and green waste from the harvest 2019 – 2020, and all the measurements were made in duplicate [32]. Finally, all of these measurements were compared with a control where no fertilizer nor compost was added, with the same conditions as the rest of the coffee plantation except with the fertilizer being added during the fertilization period of the plantation, mentioned in Table 5 - 2.

Nitrous oxide sampling to determine nitrous oxide emissions began with the first fertilization event and continued with punctual measurements throughout the crop year. Two widely used coffee varieties in the Los Santo zone were considered during sampling in Costa Rica, Geisha

(Panamanian Geisha) and Catuai. Therefore, it was considered relevant to find a relationship or similarities between the coffee variety, the amount of fertilizer applied, and the fertilization period of each variety. The principle of the measurement this technique used in this study for N_2O quantification was based on covering an area of soil with a closed, sealed chamber, allowing gas exchange between the soil and the atmosphere [37]. The gas concentration is expected to increase inside the chamber due to Fick's first law, which explains that gas flow is dependent on the concentration gradient and the diffusivity of the soil [15].

For the gas sampling, plants were selected randomly by moving in a zigzag direction to obtain random selection within the plot and choosing coffee plants of a similar age, according to the information provided by the farmers and the height. The chamber for the gas collection was placed not more than a 15 cm distance from the plant stem. The distance of the chamber was mainly for the fertilization line that is performed over that distance from the plant. Figure 5-3 shows how the selection was considered, since the fertilizer was applied to the plant's surroundings (not further than the diameter of the coffee plant leaves). All direct emissions of N_2O from SNF were calculated according to the equations suggested by the Food and Agriculture Organization (FAO) [38]. Direct emissions of N_2O from SNF:

$$Direct\ emission_{N2O} = N * \frac{44}{28} * EF_1 \text{ unit: [kg-N}_2\text{O/year]} \quad (1)$$

where: N = Nutrient consumption of N-fertilizers [kg-N/year], added to the coffee plant per year, 44/28 = conversion value of emissions from kg-N_2O-N to kg-N_2O-gas; EF_1 = 0.01; emission factor for N_2O emissions from N inputs, kg N_2O-N/kg N

Direct emissions of CO_{2eq}:

$$Direct\ emission_{CO2} = Direct\ emission_{N2O} * GWP \quad (2)$$

unit: [kg-N_2O/year]

where: GWP = 310 (100 to 110 years lifetime global warming potential)

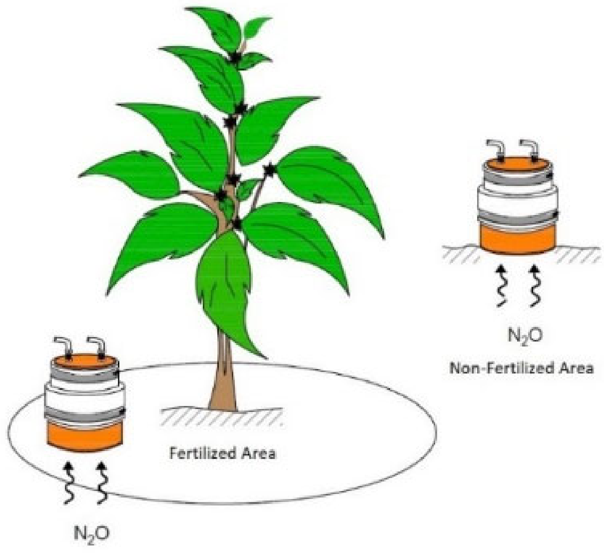


Figure 5 - 3: Chamber setup for the field experiments in the fertilized area.

Statistical analysis via a one-way analysis of variance (ANOVA) test was carried out to investigate the relationships between emissions rates and the types of fertilizer in a period. In addition, the Tukey HSD test ($\alpha = 0.05$) was used to assess significant differences between the treatments.

5.4. Results and Discussions

Overall emissions of N_2O are presented as (i) punctual emission N_2O fluxes during a set period in a botanical garden in Germany, with the standard fertilization, dose, and frequency, without any alteration in the fertilization process; (ii) punctual emission N_2O fluxes measured on a coffee plantation in Costa Rica from 2019 to 2021, without any alteration in the fertilization process taking place at a different time of year: (iii) field trial experiment in Costa Rica in a plot of a coffee plantation, where two types of SNF were tested and compared with a soil amendment and a control; (iv) direct emissions (CO_2eq) from SNF additions.

Regarding the soil analysis, ultisols represent 21% of the Costa Rican territory; they are formed with high ambient temperature, with precipitation exceeding evapotranspiration, and having as the main feature the formation of an argillic horizon with low base content and accumulation of alluvial clay [39]. In response, these types of properties and this type of volcanic region with ultisol soils are often appropriate for coffee cultivation due to the naturally high soil fertility and constant fertilization [40]. In ultisol soils, there are usually medium-to-low organic matter contents. Likewise, CEC can be very dependent on the organic fraction. Depending on the type and amount of clay, the CEC of the mineral fraction is usually low [41]. Low differences in soil properties were seen between A (soil control area), B (soil control area without pesticides), and C (soil with 40% fewer N-based fertilizers and compost application) plots. Both soils had low pH and moderate values of exchangeable Ca, Mg, and K. pH plays an important factor in N_2O emissions, especially when the pH is acidic [42]. Soil pH plays a role in controlling the nitrification and denitrification rates, mainly during the N_2O production influencing the microflora and N-transforming bacteria [43]. For instance, under alkaline conditions, the end products of the nitrification process were N_2 and low N_2O production [44].

Soil moisture is the main parameter for emissions, enhancing the microbial activity in the soil [45]. In addition, studies have reported increased N_2O emissions after applying N fertilizer, especially with high soil moisture [18]. Therefore, expected higher N_2O emission rates were found in wet seasons or during soil moisturization. Some researchers state that agricultural soils produce N_2O during the growing season due to the mineralization process of organic matter [46].

Regarding the statistical analysis, significance probabilities of $p \leq 0.35$ for the botanical garden experiments, $p \leq 1.8 \times 10^{-05}$ for comparing the varieties of coffee Catuai and Geisha, and $p \leq 4.83 \times 10^{-04}$ were used for all mean values for the fertilization trial results. Pairwise comparisons of the means using Tukey's HSD revealed nonsignificant differences between the conditions for the botanical garden (Figure 5 - 4). Contrary, for the Figure 5-5, Tukey's HSD revealed significant differences between four conditions (Geisha in 2019 and Catuai in 2021, Geisha in 2020 and Catuai in 2021, Catuai in 2019, and Catuai in 2021, and Catuai in 2019 and Catuai in 2021). The results shown in Figure 5-6 indicate a significant difference among F1 and F2, F2 and TC, F2 and SA means, at a 5% level of significance (Type I error, alpha).

For identifying the behavior of the nitrous oxide emissions on coffee plants, the first measurements were taken in the nursery greenhouse and Moorish greenhouse on 12 different spots before a fertilization event, in a continuous period of 60 min, with the portable device calibrated with ambient air. Figure 5 - 4 shows the variations in [g/m^2*h] of the 12 spots of the measurements taken in July 2019. There was continuous irrigation applied weekly during the current year, with a mixture of water and fertilizer to help the growth of the coffee plants and other species. In the nursery and the Moorish greenhouse, the plants are maintained under controlled conditions. The dosage is exemplified in Table 5-2 under the percentage of fertilizer used in the nursery greenhouse in the botanical garden for the fertilization. The irrigation is performed once per day with around 100 mL of water per pot, and the temperature ranges between 20–25 °C daily to maintain the moisture and simulate tropical weather. The emission rates were calculated to obtain specific N_2O emission fluxes from coffee plants under controlled conditions (irrigation, humidity, temperature and, fertilization), meaning an artificial ambient condition that simulates tropical conditions (high humidity) typical of the coffee monoculture regions. This value calculates the theoretical N_2O emission from a whole hectare, the emissions rates from a common density of coffee plants in monocultures (5000 to 6000 plants/ha), and the CO_2 equivalent from the examples mentioned, knowing the theoretical impact on the environment as GWP gases.

Nitrogen fertilizer dose is the variable with the greatest impact on the magnitude of N_2O emissions in coffee crops [47]. Therefore, it is important to establish the response of the emission in terms of the nitrogen dose used. Figure 5 - 4 shows small differences between each of the measurements, where the highest values were found in the small and medium plants compared to the values of the adult plants. This tendency is due to the small and medium plants receiving continuous irrigation, and their fertilizer and emission are concentrated in a smaller area (because they are in pots), whereas the adults were planted in soil in the Moorish greenhouse. In contrast, the adult plant is planted in the soil and receives less irrigation than the rest in the greenhouse.

Figure 5 - 5 shows the results of N_2O–N fluxes in the two varieties of coffee measured. The highest emissions reported in 2019 were after one month of fertilizer application in July 2019, with N_2O–N fluxes between 0.1 – 0.25 g/m^2 h. The lowest measurement was in 2020, with values below 0.1 g/m^2 h for both varieties experiencing no rain during those months. On the other hand, in 2021, the Los Santos zone experienced an atypical rainy period in March. Hence, the emissions were higher in that year than in 2020, reporting the highest emissions between 0.3 – 0.5 g/m^2 h of N_2O–N fluxes. Other studies show similar behaviors, where high N_2O emissions have been found at high soil water content, depending on water-free pore space in the soil and water availability [48].

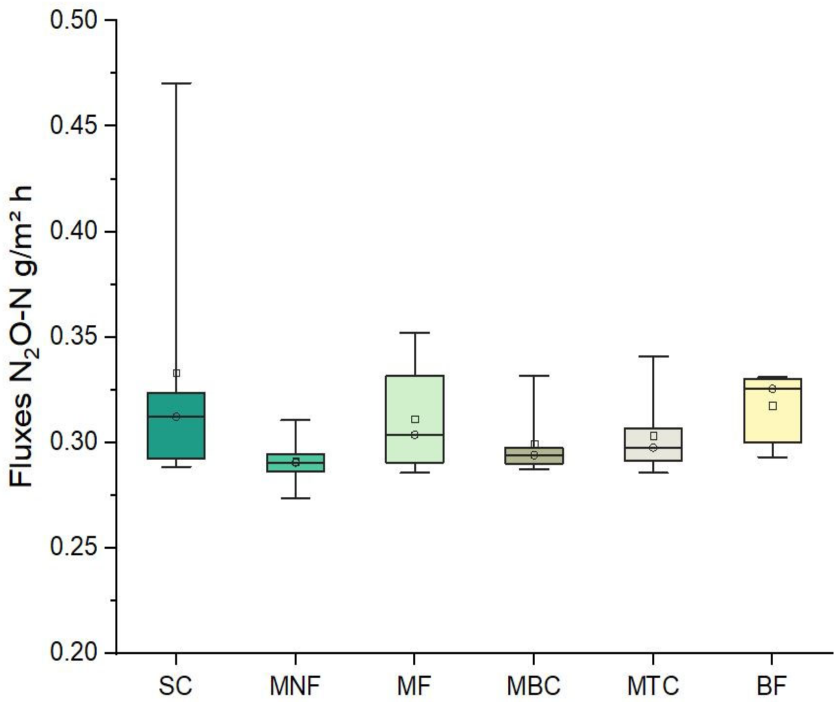


Figure 5 - 4: Boxchart summary of nitrous oxide fluxes in the botanical garden. SC: Small-sized coffee plant; MNF: small-sized coffee plant without fertilizer; MF: small-sized coffee plant with fertilizer; MBC: medium-sized plant (bottom); MTC: medium-sized coffee plant (top); BF adult-sized coffee plant with fertilizer; error bars represent the standard error of the values (n = 6).

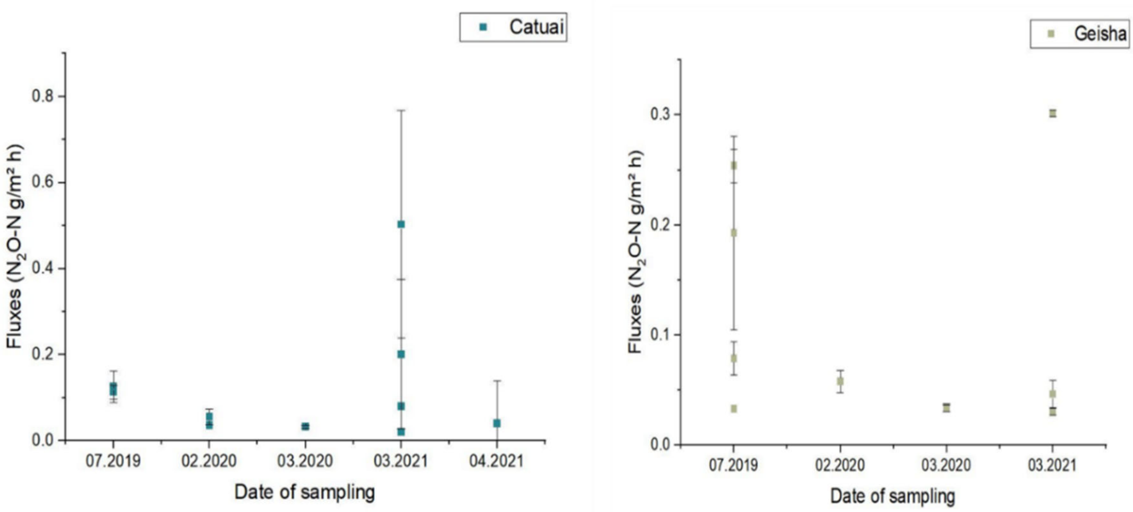


Figure 5 - 5: Nitrous oxide emissions in Geisha and Catuai. Values are the means. Error bars represent the standard error of the mean (n = 2).

N_2O–N fluxes after applying nitrogen fertilizer were unstable during the first days after fertilizer application, and were of a greater magnitude when physical mixture fertilizer was applied. Similar behavior has been observed in previous research [49], where emissions are estimated to decline with time after fertilizer application, reaching a baseline level independent of the amount applied. Regarding the compost addition as a soil amendment, it was found to have the lowest emissions during the experiment. Generally, in soil amendments, most of the nutrients are in an unavailable, organically bound form. Therefore, there is an uncertainty in the quantity of available N since the organic N is not directly available [50].

Nevertheless, the advantage of using organic soil amendments is that the release of plant-available nutrients from composts can be considerable over time. Furthermore, the frequency of fertilization can be reduced in the long term since nitrogen is stored in soil altogether in the organic form [51]. Studies imply that in soil amendments, soil organic carbon increased by 90% compared to soil amendments with chemical fertilizers, increasing the physical fertility of the soil and enhancing available K, P nutrients, and especially organic carbon, with positive effects on soil biota [52,53].

The geography in the Los Santos zone and the high latitude coffee production is due to the coffee being grown in a mountain area. If this practice could be replicated in another area, where, for example, fresh manure could be available for addition into the soil as a soil amendment, composted manure would have several advantages. For example, finished compost used in the fields is able to reduce the number of weed seeds that are able to grow, and it is low in pathogens and parasites [34]. Compost stabilizes the organic matter, and even if has a slow release of nutrients, it is recommended in some studies since it detrimentally decreases the emissions of N_2O, as is shown in Figure 5 - 6 [54,55]. Concerning the pattern of the emission of N_2O mentioned before, it is not linear, and shows that when the amount of nitrogen fertilizer applied to the coffee crop is increased at levels higher than the crop requirements, the emission of nitrous oxide also increases. The excess of nitrogen and its interaction with different conditions, such as soil moisture content, enhance the generation and subsequent release of N_2O [56].

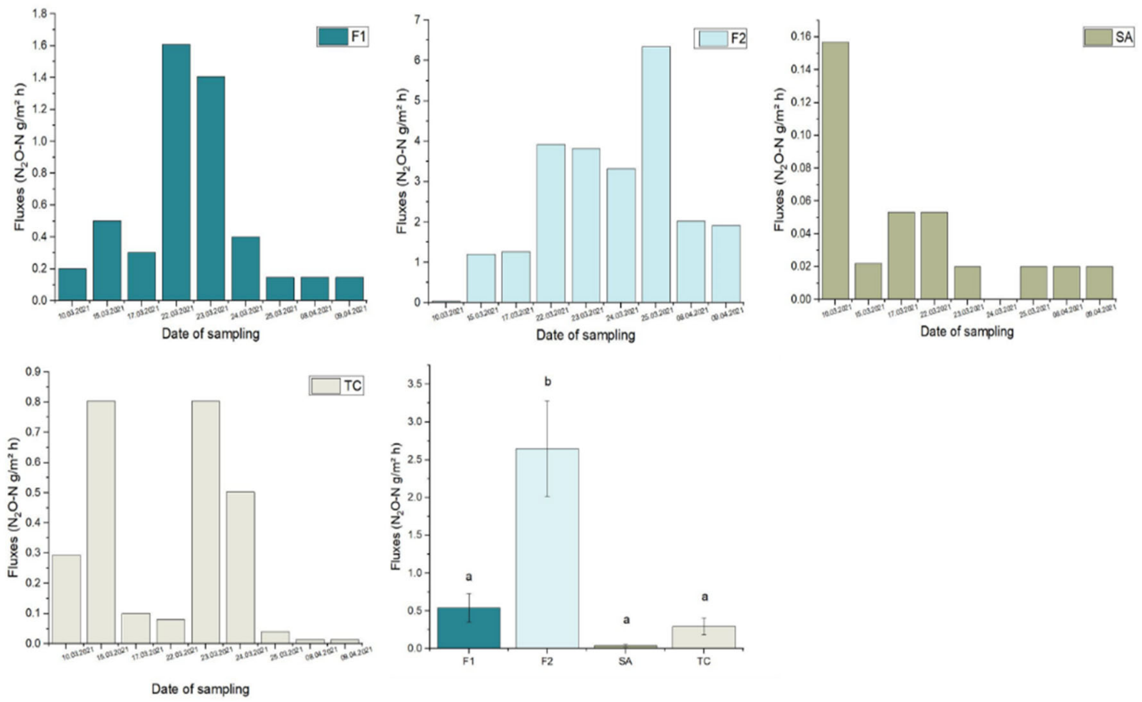


Figure 5 - 6: Nitrous oxide emission fluxes in a field experiment. SA: Coffee byproducts compost (soil amendment); F1: fertilizer 1; F2: fertilizer 2; TC: control. Values are the means. Error bars represent the standard error of the mean (n = 2). Barplot for one factor in R for all the treatments with the mean values and the standard error of the means.

According to the National Meteorological Institute in Costa Rica (IMN), the Intergovernmental Panel on Climate Change (IPCC) standards, where 1% of the total N applied annually is advised for calculating the N_2O emissions, should be taken into account [57]. For instance, in the coffee mill, the level of SNF consumption during 2019/2020 harvest was 953 kg/ha, with a contribution of 205 kg/N ha^{-1} y^{-1} [58], and for organic coffee pulp was 248 N kg ha^{-1} y^{-1} [19].

Therefore, direct N_2O emissions from the coffee plants in the botanical garden were estimated as 5.01 3 – 10.1 kg CO_2 eq yr^{-1} and for the coffee plantations as between 487 – 990 kg CO_2-eq yr^{-1}. If we compare these results, they do not differ from other studies, where they show, in general, total GHG emissions for Arabica coffee processing of 1.804 t CO_2-eq yr^{-1} [59]. It has been estimated that a coffee plantation possesses 1.02 kg of CO_2e/kg of green coffee [23]. Finally, the approach of the present study concerns an environmental assessment of the applied nitrogen fertilizer and its relationship with climate change. The long-term application of nitrogen fertilizer affects the nitrogen cycle and the microbiota in the soil. Therefore, the overuse of chemical fertilizer can harm soil quality and microbiota. Furthermore, the long-term application of chemical fertilizers can significantly reduce soil pH, which is closely associated with decreased bacterial diversity and significant changes in bacterial community composition, where compost could prevent this event due to the SNF [60].

5.5. Conclusions

This study attempted to estimate the N_2O–N emission fluxes in a coffee mill in Costa Rica, by the measuring of punctual fertilization events during the coffee fertilization cycle and the effect of two types of fertilizers used in coffee plantations. The methodology developed in the botanical garden for the first measurements and the setup under controlled conditions were achieved and reflected in the field experiments in Costa Rica.

It was determined that the highest N_2O emission events were found shortly after the fertilizer application, with a significant decrease from the third week after application. A negative relationship was found in terms of the amount of N_2O emission flux and rainfall, where the fluxes increased after a rain event. It was determined that there is N_2O emission even without nitrogen fertilizer application, although less than the other treatments. An increase in nitrous oxide emissions was also detected concerning the type of fertilizer applied. Physical mixture fertilizer showed higher emissions than chemical fertilizer. A recommendation would be to consider the year when the fertilizer is applied, to avoid the sudden burst of nitrous oxide when the rainy season in Costa Rica occurs. Compost (SA) showed low N_2O emission in comparison with the synthetic fertilizers. Further research is suggested to observe the emissions of SA in the long term, to assure emission reduction in the plots by the usage of organic soil amendments. In addition, fertilizers could reduce the N-leaching losses and the contribution of N_2O emissions in the long term, considering slow-release nitrogen or nitrification inhibitors. It is suggested to carry out this type of evaluation for periods longer than one year. Besides, continuous and simultaneous measurements for at least three different coffee plants per day could offer more robust data. Nitrous oxide emissions can be obtained in future assessments under the changing influence of climatic variables during the day, which usually differ between years and seasons.

Thus, we recommend to use these equations to estimate nitrous oxide emissions from fertilization in coffee cultivation in Costa Rica with a higher degree of confidence. In addition, it is advisable to investigate the effects of farming practices and management focused on the efficiency and use of nitrogen in coffee plantations, in order to gather more data and to understand the long-term effects and their relationships.

Author Contributions: Conceptualization. M.S.M.R., M.R.; methodology. M.R., M.S.M.R., and M.K. validation. M.R., M.K., and M.S.M.R.; formal analysis. M.S.M.R., M.R., investigation. M.S.M.R.; M.R. and M.K.; data curation. M.S.M.R., M.R. writing—original draft preparation M.S.M.R., M.R. supervision. M.R., M.K., M.S.M.R. project administration M.R., M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been financed by the Coffee Mill Coopetarrazú R.L in Costa Rica.

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Acknowledgments: We gladly thank the personnel of Coopetarrazú R.L and the Wilhelma-Zoo and botanical garden for giving us the space to perform the experiments in their commodities, and furthermore for providing the information necessary for the experiments and methodology. Moreover, we gladly thank Daniela Castro Herrera for reviewing the statistical analysis and calculations, the personnel laboratory assistances, students, and colleagues of the Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) at the University of Stuttgart.

Conflicts of interest: The authors declare no conflict of interest.

5.6. References

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6. General Discussion

The research was published in three peer-reviewed papers, and the main findings were thoroughly discussed in each paper to present an understandable and compact interpretation of the results. In addition, the sections summarize the dissertation results and discuss the significant improvements in waste management, the quantification of emissions and its carbon footprint during composting and fertilization, good agricultural practices, a circular economy approach, and certain limitations during the study.

6.1. Summary during the modification of the traditional coffee by-products, waste management, and composting

Today, Costa Rican coffee producers face the same challenges as agricultural producers worldwide in maintaining adequate crop production, and they must change their approach to continue their activity. Currently, SNF prices have nearly tripled due to various factors, including COVID-19 and high transportation costs due to fuel price increases. For example, the SNF prices provided by mill personnel from 2021 to 2022 increased by 123 percent to 152 percent for every bag of fertilizer (46 kg per bag). Soil amendments based on proper waste management and valorization are essential to reducing the use of industrial fertilizers and gradually decreasing reliance on these products in the fields.

Among the five factors to consider to provide sustainable alternatives during the management of coffee by-products within the composting area are climate, composting time, processing area, pathogen vectors, and how viable it is to collect that amount of material. In total, all factors have to be considered as a link and not be considered as each factor separately. The climactic part is relevant as most coffee pulp composting areas are entirely open. In addition, the areas are divided within the total area of the farm, and the rotation of space must be very systematic so that the maximum amount of pulp can be composted for each crop. The composting time is linked to the country's summer season, especially since it is an open area for composting. It is of utmost importance that the material does not get wet, increasing the proliferation of flies and pathogens in Costa Rica.

One of the major concerns regarding these vectors is the proliferation of the Stable Fly (*Stomoxys calcitrans*). This fly mainly affects livestock. It does not transmit any disease but mainly affects animal welfare and causes substantial economic losses in livestock activity (Baldacchino et al., 2013). Furthermore, the harvest is once per year in summer, meaning that the collection of green waste materials must also be foreseen before the harvest. Therefore, the collection plan must be quick and efficient to collect and protect the material from getting wet during winter.

Considering that the plan is to scale up to 37,000 tons of pulp in the future, it was decided to start with scalability. During the first phase, 2 tons of coffee by-products were used, followed by 150 tons in the second phase, 525 tons in the third phase, and 510 tons in the fourth phase. This was mainly to give the proper training to the cooperative's staff and the study by giving them the necessary recommendations for the collection materials. Finding structural materials from the surrounding area was one of the biggest challenges because the mill could use coffee husk to heat its ovens. However, this leads to subsequent challenges since, in 8 to 12 weeks, the compost treated as 100% with coffee by-products is not thoroughly composted. In the end, a mixture of husk and dry pulp is left as an alternative product for the producers. The husk being small and low in weight (density of 260 kg/m^3), it is observed that the material adheres to the pulp (figure 6 - 1) and, in the end, does not provide the porosity sought for the system to have aeration during the process. This was one of the main reasons it was necessary to look for alternatives to start the composting process. The husk performance was observed during the first phase of the tumblers experiment. The same pattern was observed in the field control during the trial in Costa Rica (figure 6 – 1 B).

One of the key elements influencing the composting process and the characteristics of the final product is the C/N ratio. The ideal C/N ratios for composting most materials range from 25 to 30. A C/N ratio of roughly 30 is optimum for ensuring carbon energy intake while promoting rapid microbial development (Kumar et al., 2010b; J.-M. Zhou, 2017). Moisture is a factor that affects microorganisms. Low initial moisture values (less than 30%) can cause the compost to dehydrate rapidly, pausing the biological process and resulting in physically stable but biologically unstable compost.

In contrast, compost becomes anaerobic when the relative humidity is high (greater than 80%). An ideal moisture range for composting is between 45 and 50 percent. Less than 30% of moisture will inhibit bacterial activity, and more than 65% will cause the compost's porosity to decrease, leading to anaerobic development and unappealing odor emissions (Ameen et al., 2016). The bulk density during composting measures the mass of the material contained in a specific volume (Agnew & Leonard, 2003). Mechanical characteristics in the compost, such as strength, porosity, and compaction ease, are also influenced by density. Wet bulk densities typically vary from 500 to 900 kg/m^3, while dry bulk densities typically range from 100 to 400 kg/m^3. Higher bulk density readings indicate a greater mass and a smaller porosity and air volume. On the other hand, a low wet bulk density may signal excessive substrate aeration and, thus, a decline in the available water portion (Agnew & Leonard, 2003).

External factors that affect the composting process include the environment, technique employed, and raw materials used during the study. However, it was also taken into account to use the same amount of materials, for example, as green waste, in order not to add even more external factors attributed to the performance of the composting process in Costa Rica.

According to (de Bertoldi et al., 1982), organic material can be composted in a wide pH range (3 – 11). Between 5.5 to 8 is the optimal range. The optimal range for the development of microorganisms is close to neutrality. As opposed to bacteria, fungi are more resistant to remote neutral pH. The pH may drop during the initial composting stage due to the organic acids generated during the breakdown of simple organic substrates and the volatilization of the initial ammonia. The pH then rises due to mineralization and the breakdown of easily degradable organic molecules. The temperature impacts pH evolution, encouraging the volatilization of ammonia (Ameen et al., 2016; Simandi et al., 2005; Sundberg, 2005).

Compost amendments may activate a variety of natural disease-suppressing mechanisms against plant pathogens, compost properties result in the compost having positive effects on plant growth (Simiele et al., 2022). Therefore, composting is a promising alternative for the environment that produces valuable products with a positive impact on soil and plants (Milinković et al., 2019). Compost must be stable and mature in order to be effective as a plant amendment and fertilizer source (W. H. Luo et al., 2014). There are two different ways to describe compost quality: The first is based on the idea that an initially unstable organic matter transforms into a stable organic matter after composting. The biodegradability of organic materials and their level of humification are used to determine the compost's degree of stability (Ameen et al., 2016; Sudharsan Varma & Kalamdhad, 2014). The second strategy takes into account how compost affects plants. The level of maturity in this case was related to the absence of plant damage from compost use, such as the adverse effects of adding immature compost to the soil on plant germination, growth, and development. In other words, the phytotoxicity of the compost is still the best predictor of its development in this aspect (BGK, 2017; Siebert et al., 2012).

Figure 6 - 1: Coffee Husk and Coffee pulp. A: Performance in the tumblers, B: performance in the Field in Costa Rica.

Temperatures and pH profiles were made during application and model suitability. One of the results before (San Martin Ruiz et al., 2020), and one of the reasons why only the structural material and grass were considered for the published tests and research, explicitly refers to the results obtained as shown in the Appendix. Table 6 - 1 shows a summary of the treatments presented (San Martin Ruiz et al., 2020,2021). During the temperature behavior, treatments 1, 2, 6, and 7 obtained the most similar profiles to the temperature profiles according to the BGK. The husk was added to some piles in the current treatment of the mill. This occurs when the mill primarily obtains husk that cannot be entirely used in the ovens for roasting the coffee, so therefore the husk is added into the piles to make use of it. The suggestion to add a material for the coffee pulp composting process was positive since the mixtures resulted in better temperature profiles than the Control. For example, treatments T3 and T4 improved performance even when the pile was made using coffee husk as a structural material. All the proposed tests exceeded the thermophilic temperatures within ten days of the composting process. For example, if the compost is heated up to 40°C or 50°C, it can be deduced that the ingredients contain adequate nitrogen and moisture for rapid microbial growth. By plotting the compost temperature over time, how much decomposition has progressed visually over the material can be seen. A well-constructed composting system will heat up to 40°C or 50°C in two to three days. As the easily decomposed organic matter is depleted, the temperature begins to drop, and the process slows considerably (Naorem et al., 2021). Figure 6 - 2 shows how the composting process looks when just coffee pulp is composted and when the coffee pulp is mixed with GW during the first four weeks.

Figure 6 - 2: Coffee pulp composted on the left, and coffee pulp with GW on the right with the same time of composting weeks.

As the compost begins to cool down, turning the pile usually results in a new temperature spike due to replenishment of the oxygen supply and exposure of organic matter that has not yet fully decomposed. After the thermophilic phase, the compost temperature drops and is not restored by turning or mixing. At this point, decomposition is taken over by mesophilic microbes through a long maturation process. Although the compost temperature is close to room temperature during the maturation phase, chemical reactions still make the remaining organic matter more stable and suitable for plant use (Clarence G. Golueke, 1973). In addition, the pH change in the Control is observed to be abrupt after the first three weeks compared to the rest of the proposed treatments. Given these first results, it was decided to use only structural material and grass to follow up on the medium scale of the study, which was also mentioned in detail in (San Martin Ruiz et al., 2020).

The influence of pH, nutrient availability, activities, and nature of the microbial populations affect the composting process by affecting the microbial population and controlling the availability of nutrients to the microorganisms. The optimum pH is between 6.0 and 7.5 for most bacteria. The pH indicates compost stability and phytotoxicity. - Stability would be in the range of 5.5 to 8.0 (Sundberg et al., 2004, 2013; Taiwo & Oso, 2004).

The different mixtures were compared in a physicochemical approach during the design application, following the composting parameters and visually as the material changed through the weeks of composting. Figure 6 - 3 shows how the different treatments are observed from TC to T5, where an evident degradation of the coffee by-products can be seen in the treatments compared to the control during the first four weeks of treatment. That is to say, the processes to optimize the composting process, its degradation to the maximum, and using the most considerable amount of coffee pulp are the 50 GW and 50% CP (T5).

As a second recommendation, the treatments could be used as an alternative for the mill if it is not possible to collect the necessary GW to perform the processes in the future. It is also demonstrated that when composting 100% CP, the coffee pulp is not recommended because of its high lignin and cellulose content.

Because of the physicochemical characteristics mentioned (San Martin Ruiz et al., 2020), the material takes time to be heated so that the microorganisms can work and degrade the organic matter. This leads not only to the consequences of emissions but also to the vectors of pathogens. Recall that the pulp is about 85% WC, meaning that when it is piled up, the edges are colder, making it an exceptional host for pathogen vectors, having adequate climatic conditions, sugars, and protection necessary to lay eggs and increase future larvae. In addition, it has been observed that when the coffee pulp is homogeneously composted, the material after eight weeks, due to the climatic conditions in summer, the pulp is dried and not degraded. As a result, the mechanical turners act, and the pulp is fractionated into smaller pieces without finishing its process. This leads to later consequences when the material is used in coffee plantations.

One of the significant challenges was the final disposal of the product in the coffee plantations. (San Martin Ruiz et al., 2021), explained the control according to composting parameters is considered unfinished. This material is transported and added to the coffee plantations. The difficulty was that fly larvae were generated inside the crops after a few months and the first rains.

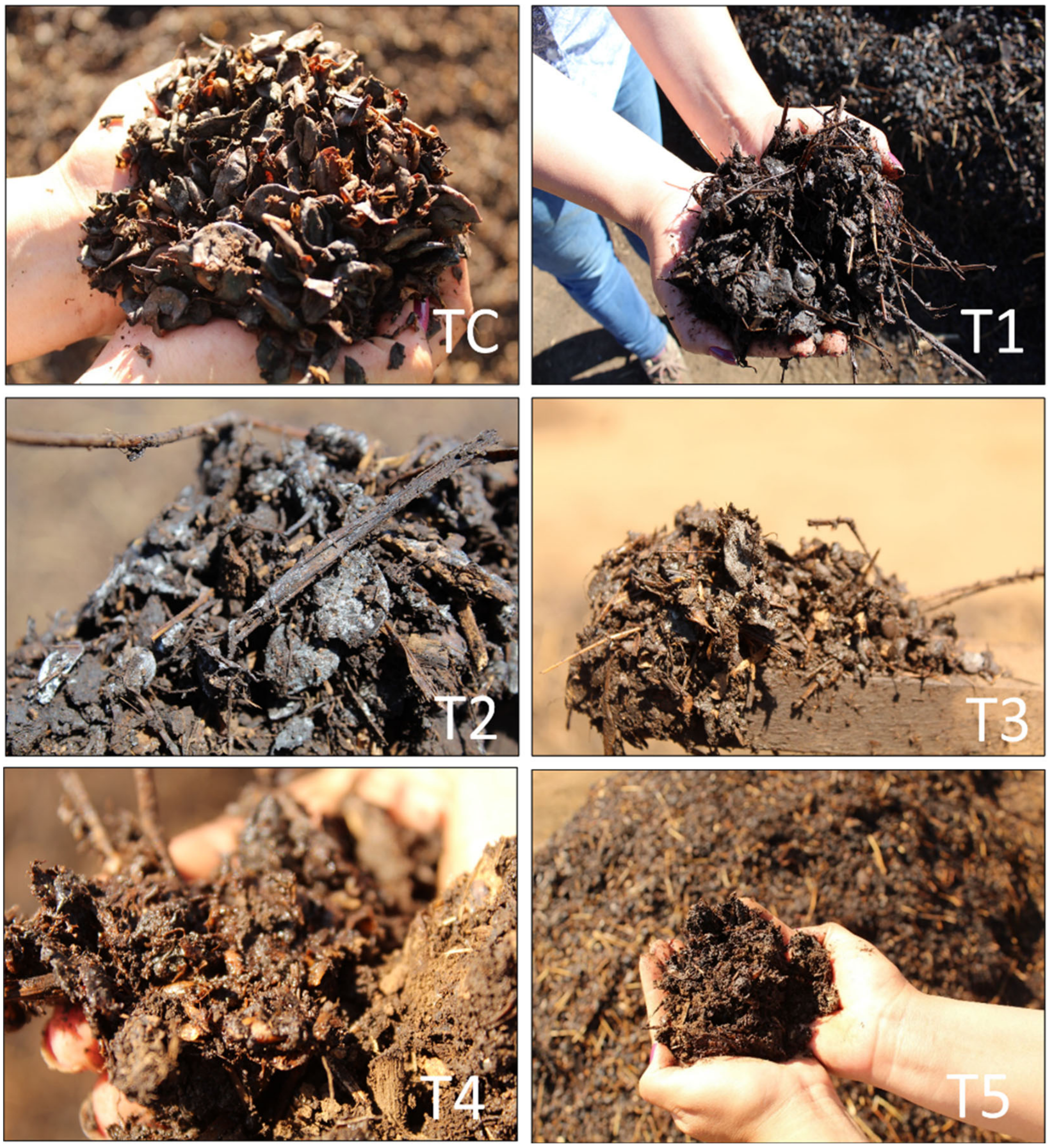

Figure 6 - 3: Coffee pulp and GW during the composting process during the application and model suitability for the process. TC corresponds to the control (100% pulp), T1 - T5 corresponds to 20%, 25%, 30%,40% and, 50% of GW mixture respectively.

Table 6 - 1: Summary of the treatments and mixtures based on volume percentage among all the research developed.

1. Basics of the process		**2. Application and model suitability for the process**			
Treatment	**Windrow Percentage Vol %**	**Treatment**	**Windrow Percentage Vol %**	**Treatment**	**Windrow Percentage Vol %**
T1	50% CP- 50% CH.	T1	60% CP - 40% GW.	T6	Treatment 1 under roof.
T2	50% CP - 40% CH- 10% GW.	T2	50% CP- 30% GW - 20% processed CP.	T7	Treatment 2 is under the roof.
T3	50% CP- 50% GW.	T3	TC : 99% CP - 1% CH on edges.	T8	40% CP -35% GW - 20% processed CP - 5% ashes.
T4	50% CP- 50% GW	T4	85% CP - 15% CH.	T9	Treatment 5 under the roof.
		T5	33.3% CP - 33.3% sawdust- 33.3% processed CP	T10	50% CP - 20% GW - 10% sawdust - 20% processed CP

3. Design application		**4. Reproducibility of the design**	
Treatment	**Windrow Percentage Vol%**	**Treatment**	**Windrow Percentage Vol %**
T1	80% CP – 20% GW	T1	70% CP - 30 % GW
T2	75% CP – 25% GW		
T3	70% CP – 30% GW	T2	80% CP - 20% GW
T4	60% CP – 40 % GW		
T5	50% CP – 50% GW	T3 (TC)	100% CP
TC	100% CP (Control)		

CP: Coffee Pulp, GW: Green Waste.

As shown in figure 6 - 4, the material compacted and formed a layer, causing difficulties with fertilization according to the agronomists of the mill, since sometimes the fertilizer was applied over the layer made of the control compost in the coffee plantations.

As a result, the plant could partially absorb the fertilizer. After implementing the new methodology, tests were carried out on a few plantations to verify that the Control's vectors did not occur with the proposed compost. However, no-fly nuisance or compaction of the material was recorded after a few months of use.

Figure 6 - 4: Coffee pulp without proposed treatments on the soil surface of the coffee plantations. The material is compacted and forms a layer in the coffee plantations. The coffee pulp can also be seen as not fully degraded in the actual composting process.

Furthermore, improvements were made during the compost pile formation process. Previously, the coffee pulp was taken immediately after the de-pulping process was finished for the day. The coffee pulp was left overnight in a loading zone within the coffee facility during the trials. The material could drain overnight and be taken to the composting area the next day, resulting in a positive outcome in the trials. As a recommendation, the compost piles were built with at least half a meter of space between them.

This suggestion was made not only to provide separation between the various treatments and mixtures but also to avoid that when mechanical movements occurred for the weekly turning, the piles would have a space, preventing pathogen proliferation between the rows of compost piles. Figure 6 - 5 depicts the evolution of the composting process and its management.

Figure 6 - 5: Before: Piles before implementing the methodology. After: methodology implemented with the proposed mixtures and space among the piles. Before, there was a lack of space between the piles, so water from the pulp accumulated between each pile. Thus, facilitating the growth of insects and diseases, after that, the piles were separated, and with the GW material added, the piles did not experience any leachate during the process compared to before treatment.

The emissions from field deposition were depicted in (San Martin Ruiz et al., 2021). It is important to note that the cooperative is reducing the use of field deposition. Not only because of the environmental impact in terms of emissions but also because of the cooperative's ability to occupy the composting area efficiently by implementing this new alternative and waste management. In addition to the mill where the study was done, the same tactics are used in other industries throughout each harvest, primarily due to a lack of space.

For example, it was necessary to wait 12 weeks for a compost pile to complete its process. With the implementation completed, the mill can now use that space to form half of a new compost pile during the same compost period. Moreover, when it is not composted and is accumulated in open fields, there is no positive effect on CH_4 emissions or its utilization on coffee plantations as a product.

When the material has been adequately composted, its volume is reduced by at least half within a few weeks (Cáceres et al., 2015; Michel et al., 2004). As a result, what used to be deposited in the field due to a lack of space can now be taken to the composting area and given a waste value to avoid emissions and include proper waste management.

The field deposition is depicted in figure 6 - 6. They appear to be a small field hill at first glance because, once loaded, the area is covered with soil, and in the upcoming years, only the grass can be seen as if it were a standard field. Figure 6 - 6 - (3), on the other hand, depicts the contrast between the newly deposited pulp and the green grass surrounding it, which was deposition from the previous year's field.

Figure 6 - 6 - (2), on the other hand, shows that when the pulp is dug up from previous harvests, it retains its orange color while remaining intact. When pulp is not correctly treated, it converts anaerobically, emitting considerable amounts of methane and remaining in a pile for extended periods without degradation.

Based on earlier research carried out at the same Mill (San Martin Ruiz et al. 2018), measurements of CH_4 were made in the open field depositions during the thesis. The main goal was to determine whether the emissions from the coffee pulp control used in the composting process resembled those produced when the pulp was piled up for field deposition.

The aim was to further support the idea that when pulp is combined with other organic materials, CH_4 emissions decrease. This is the reason that during the initial tests, the goal of the first publication of this thesis (San Martin Ruiz et al., 2020),) was to examine how the pulp behaved in comparison to other materials and the maximum that the cooperative would consider mixing for use in the future (material collection capacity). The values obtained during the measurement stage in Germany are less than all the values measured throughout the investigation because an FTIR device was also used to conduct the measurements; the pile size was only 6 m^3 compared to the field trials in Costa Rica and under different conditions (covered area of composting, pre composted green waste from the composting plant, the coffee pulp was dried and then humidified for the trial and weather conditions)

After that, to be able to compare the decrease of emissions versus the proposed management, the intention was to further corroborate the decrease of emissions when the pulp is mixed with other organic materials. This is why during the first tests and where the first publication of this thesis was aimed at (San Martin Ruiz et al., 2020) was to study the behavior of the pulp mixed with different materials and the maximum that the cooperative would be willing to mix to be used in the future (material collection capacity). For this reason, once advances were found based on the first publication, these materials were tested at different percentages. After that, to compare the decrease of emissions versus the proposed management was the next aim of this research.

When the results are compared, for example, coffee pulp in open field deposition as fresh or in the first year emits 25% less than in the first weeks of composting when only coffee pulp is in a pile. As a result, the emissions in the open field deposition and during the composting process with the actual treatment have similar values. Meanwhile, it has been emitting odors and high CH_4 concentrations for many years (Raphael & Velmourougane, 2011). As a result, this thesis does not endorse this practice.

In total, EF were compared between the years that the open field depositions are in the cooperative when the pulp cannot be composted and the total composting time of 10 weeks in Costa Rica. Table 6 - 2, which lists all of the methane emissions measured during the investigation, displays the findings. The results indicate that when the pulp has been buried for more than two years with an EF of 1.684 g CH_4/ kg green coffee, TC with 0.210 g CH_4/ kg green coffee has similar results. With this, it can be confirmed that the pulp, when composted uniformly, creates anaerobic zones, simulating the effect of deposition in an open field.

Without accounting for waste management, the overall carbon footprint of coffee production along the entire supply chain is 4.82 kg CO_{2e} kg^{-1} green coffee (Noponen et al., 2012; Vera-Acevedo et al., 2016). According to ICAFE, the processes used in Costa Rica to produce 1 kg of green coffee have a carbon footprint of 1.77 kg CO_{2e}. The IPPC's (Intergovernmental Panel on Climate Change) global warming potential values of 27 and 298 for CH_4 and N_2O, respectively, were used to calculate the carbon footprint of the thesis.

An average of 0.04 kg CO_{2e} kg^{-1} green coffee was found to be released during composting, compared to 0.4 kg CO_{2e} kg^{-1} green coffee for the treatment used as a control, which involved producing compost exclusively from coffee pulp. Up to 2.1 kg CO_{2e} kg^{-1} green coffee emissions were calculated for open field deposition, which equates to almost half of the emissions generated throughout the production process.

Table 6- 2: Summary of methane emissions factors during composting and open field depositions.

Method	EF (g CH_4/kg Pulp)	EF (g CH_4/kg green coffee)
Composting trial in Germany		
Pile I	0.013	0.0001
Composting Treatments in Costa Rica		
T1	14.04	0.04
T2	10.84	0.03
T3	14.03	0.04
T4	14.03	0.05
T5	5.78	0.03
TC control 100% pulp	128.74	0.29
Open field deposition in Costa Rica (years)		
0	204.23	21.48
1	329.91	34.71
2	754.08	79.33
3	217.74	22.91
4	158.36	16.66
5	494.86	52.06

Figure 6 - 6: Field deposition, 1: Field deposition covered to avoid pathogens and odors, 2; unearthed pulp after two years of burial. 3: Field deposition formation.

On the other hand, the implemented methodology reduced CH_4 emissions by 80% by adding 20% to by incorporating bulking and GW into the coffee pulp for composting 93% CH_4 reduction when 50% GW was added into the pile. One of the most critical problems is the pulp generated, dumped in farm or village streams, contaminating water bodies. It alters the chemical composition of the water and produces unpleasant odors. The release of polluted solid and liquid materials is responsible for this. As a result, there has been a national decline in the quality of human consumption and the fauna of particular streams. In addition, the discharge of solid waste and contaminated liquids degrades the quality of water streams for human consumption and wildlife.

6.2. Emissions and their relevance to the coffee sector

Costa Rica is currently trying to mitigate, verify and report certain greenhouse gases such as CH_4 and N_2O (Nieters et al., 2015). However, there are currently no reports or databases for nitrous oxide in crops to date, according to ICAFE.

Costa Rica is one of the largest exporters of coffee and has many plantations around the country. Therefore, it is essential to know the number of emissions in the crops and the sector, depending on waste treatment and the management of plantations.

Under different life cycle analyses, the coffee sector has shown that the processes addressed in the study are the two most important processes regarding emissions: coffee by-products for composting and fertilization. During this waste coffee by-product management and fertilization, the most significant emissions in the sector at the levels CH_4 and N_2O occur (Adams & Ghaly, 2007; Nab & Maslin, 2020).

These gases were measured for the first time in Costa Rica under this methodology in coffee crops. Therefore, quantifying the emissions to build the first databases in the country was an important step. Furthermore, within the methodology, we sought to develop a methodology of accessible transport and installation since the equipment and hoods should be transported via air to Costa Rica and then transported to the mill.

During the composting treatment, the first tests conducted in Germany aided in developing a methodology for monitoring GHG and the first measurements in Costa Rica. In Costa Rica, emissions were measured during the first six weeks because specific references indicate that emissions during the composting process occur during that time when mixed with GW(Hwang et al., 2020; Vergara & Silver, 2019).

The methane emissions are presumed to come from anaerobic zones, resulting from the homogeneous consistency of the material, and the not homogeneous mixed consistencies of the proposed treatments, leaving spots of the pulp as the control, although for this case, the emissions were much lower than the control.

One of the reasons is that mainly anaerobic bacteria generate CH_4 until the structural units are destroyed, and then aerobic conditions within the pile are again predominant. (Ermolaev et al., 2015; Jürgen Hellebrand & Kalk, 2001). Therefore, the proposed piles did not present higher emissions than the control. Furthermore, the piles were formed in layers (a layer of pulp, then a layer of GW, until the recommended height of the compost pile was reached, and anoxic or anaerobic states were avoided due to this proposed system for the formation of the piles.

As mentioned in the three publications, Costa Rica has only a few emission factors for composting treatment but not related to coffee pulp. Therefore, these values would be the first to start a line in the country. Based on the results obtained, it is undoubtedly recommended to use a mixture of GW to perform low emission management of composting. Within the results obtained in Costa Rica, the recommendation based on emissions, nutrients, and behavior profile during the process are to mix at least 25% to 50% GW to make the piles in the future.

About the emissions in coffee plantations and during the tests carried out in this research. It is essential to emphasize the importance of generating a previous methodology to start the measurements in the field. For example, it was necessary to consider whether the measurements would be only at the soil level or the total plant level during the tests. However, more factors must be considered at the entire plant and soil level, and more tests must be performed, especially considering plant respiration. For example, plants generally close their stomata during the night, as this is the cooling mechanism that the plant possesses (Christodoulakis et al., 2002; Habermann et al., 2019). Also, for an agronomic recommendation of the mill and security reasons of nocturnal fauna in the coffee plantations, the measurements were made during the day, always trying to measure emissions at the exact hours. In the tropical climate in that area, the temperature can reach up to 5 °C during the night, meaning that the surface soil and atmospheric temperature vary considerably during the morning.

Among the findings presented (San Martin Ruiz et al., 2021), a strong relationship was found between rainfall events and N_2O emission. One of the reasons is the increase in the soil layer, creating an anaerobic condition that incites this gas's formation (Robertson & Groffman, 2007).

On the other hand, fertilizers, physical formulas, or complete formulas (18 (N) – 5 (P_2O_5) – 15 (K_2O) - 7.3 (S) - 6 (MgO) - 0.2 (B)) must interact with water and release the fertilizer compounds. Therefore, it is logical to be emitted in large quantities, mainly since several rain events occurred in the area during the fertilizer tests. In addition, the effect of rain on the emission could be related to the availability of nitrogen in the soil.

Although rain was present during much of the evaluation period, it seems to influence only after fertilizer application. Furthermore, the literature indicates emissions can increase 3-10 times when the pH is basic (Robertson & Groffman, 2007). However, soils in coffee-growing areas are generally acidic. The pH did not vary from 4.9 - 5.5 on the coffee plantations; this was not a factor considered and monitored within the research.

The N_2O emission rates found in the Catuai variety were between 0.1 g × m^{-2} × h^{-1} - 0.6 g × m^{-2} × h^{-1}, and between 0.1 g × m^{-2} × h^{-1} - 0.25 g × m^{-2} × h^{-1} for Geisha variety. However, suppose these values are compared. Nevertheless, in that case, the measurements in coffee plantations differ. This is because the soil conditions (inseptisols vs. ultisols), pH soil (6.3 vs. 4-5), fertilization rate per year 150 of N vs. 300 N, and several applications 2 vs. 4) were different. Therefore, the values can vary from one measurement to the other.

The average emissions during the thesis were 0.04 g × m^{-2} × h^{-1} for soil amendments, 2,65 g × m^{-2} × h^{-1} for physical fertilizers, 0.55 g × m^{-2} × h^{-1} for chemical fertilizer, and 0.30 g × m^{-2} × h^{-1} for the control. Therefore, it was expected that the physical and chemical fertilizers would have higher emotions than the control without fertilizer, where a clear relationship between the fertilization event and the amount of N_2O found was evidenced.

In terms of carbon footprint, emissions for the experiments conducted at coffee plantations ranged from 1.88 kg CO_{2e} kg^{-1} green coffee when compost was used as a product to 3.5 kg CO_{2e} kg^{-1} green coffee when synthetic fertilizer was used. The results were in line with the literature, which claims that fertilization increases the carbon footprint of coffee by 0.5 to 3.1 CO_{2e} kg^{-1} green coffee when it is in the stage of cultivation.

The difference in emissions between a physical fertilizer and a chemical formula fertilizer concerning the time and period of emission was unknown in the country. Generally, chemical fertilization occurs three times a year, and physical fertilization occurs between these fertilizations. Therefore, it is evident that the physical fertilizer could reach values almost double what chemical fertilization could be during the first month of release.

In any case, it is clear evidence that both physical and chemical fertilizers emit high concentrations of N_2O if compared to an organic amendment or when the soil does not have a fertilizer recently added.

6.3. Circular economy

One of the significant challenges in the coffee sector and its type of intensive agriculture is to make a sustainable production over time, efficiently using resources and generating a lower impact in terms of ecological footprint. That is why within this project, one of the primary purposes is to instigate a waste value, wherein, in the end, it becomes a resource of significant importance for the agricultural sector, promoting a circular economy.

One of the term circular economy definitions that connect sustainable development objectives is: "*an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso level (eco-industrial parks), and macro-level (city, region, nation, and beyond) to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers*" (Kirchherr et al., 2017).

Sustainable management with compost production was thought of as a concept like figure 6-7 to implement measures within the production chain using a circular economy model involving coffee by-products to mitigate the misuse of waste management. The production and use of compost not only help at the level of a circular economy but also helps to reduce emissions, the amount of waste going to field depositions and also create a final product that benefits the soil due to the intense degradation of soils due to the lack of amendments and excessive use of fertilizer. (Bastida et al., 2015). Figure 6 - 7 shows the concept created towards a circular economy within the research proposed with coffee by-products.

On the other hand, the rise in fertilizer prices has had a high impact worldwide, with prices increasing year by year. However, the most significant increase in recent years is expected to occur in 2022. According to calculations made in collaboration with the mill's agronomists, using the soil amendment produced in this thesis will result in an estimated savings of US$371.63 per hectare per year (at August 2022 prices).

According to the Food and Agricultural Policy Research Institute, nitrogen fertilizer prices will increase by 80% by 2022 (FAPRI, 2021). With this, circularity and waste value implementation can significantly help farmers' soils, improving soils and contributing to the organic matter content.

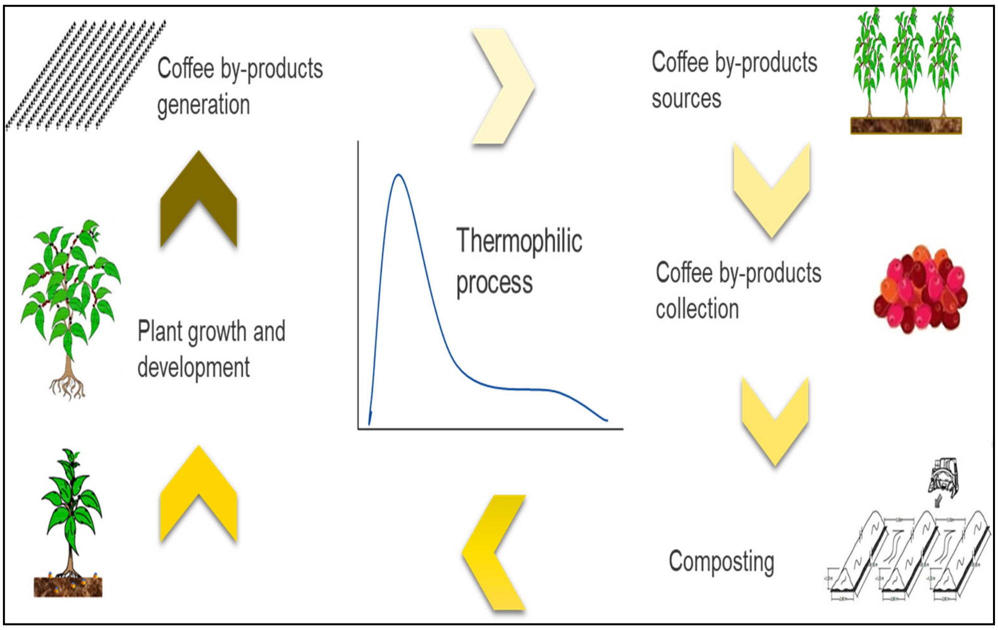

Figure 6 - 7: Coffee by-products-a concept towards a circular economy.

This would be of great advantage for the next few years as it is estimated that the coffee industry will suffer significant consequences due to climate change on coffee plantations. It is of utmost importance to conserve soil nutrients by increasing soil stability and pores, reducing compaction, and increasing water retention capacity. (Bunn et al., 2015; Pham et al., 2019) .

6.4. Implementation of good agricultural practices

Production systems can generate environmental impacts that do not necessarily manifest within the system's physical limits. Therefore, it is necessary to identify the environmental risks associated with establishing crop production and the practices and technologies that minimize them.

Within the research, storage and packaging recommendations were made. The nutrient results of the proposed improved processes are shown in (San Martin Ruiz et al., 2021). By performing a nutrient analysis, recommendations for use and amounts were proposed, giving mill staff an incentive to monitor annually during each product harvest. Furthermore, with the implementation of this methodology, the mill has the opportunity to process its residues to almost full scale, with the vision to obtain organic amendments from their residues, decreasing their environmental impact and promoting good practices within the sector.

It is essential to carry out a technology transfer. As a final part of the research, there was a training plan. As a result, the people carrying out the composting process could form piles, turn, mix, collect, sample, and measure composting parameters for monitoring adequately. In addition, pesticides during the composting process, which were previously considered necessary for the mitigation of pathogen vectors, were considerably reduced. Now with the implementation of the proposed methodology, the vectors diminished. Therefore, this problem affected the composting area, the fauna, and the population around the coffee plantation, diminishing impacts on the environment and population in the surroundings.

On the other hand, the constant use of synthetic fertilizers contaminates the soil and water, and the deficient applications degrade soil fertility. Therefore, a balanced application is necessary, and organic amendments are recommended. Manures, fertilizers, and amendments should be based on lot and crop-specific information and excessive fertilizer applications. These precautions apply to organic amendments, soil conditioners, and soil correctors (FAO,2015).

It is recommended that soil amendments be applied after a period that ensures the environment is not contaminated and primary production is not affected. This is why it is essential to use a quality product in a finished state not to cause further challenges within the plantations. Recycling pulp and making a product from it provides an organic soil amendment hat enhances soil nutrients at a low cost, reducing the need for chemical inputs. Furthermore, lowering climate-related emissions and positively impacting soil and plant growth.

6.5 Limitations

This research faced several limitations:

1. The sampling period and quantity. Since the trials were conducted in Costa Rica, one of the challenges was coordinating and estimating the behavioral patterns of climate conditions and the period proposed to conduct the measurements, especially given the travel restrictions during the global pandemic.

2. Initially, the volume of GW collected was unknown. At the start of the study, it was unclear what quantity could be collected and the amount of material available. As a

result, the amount was planned before each trial based on the amount of material available that year.

3. Composting is a relatively new topic in Costa Rica. As a result, some limitations in laboratory analysis were observed. For example, since the laboratories lacked unique technology for compost analysis, the samples had to be shipped to Germany for several analyses.

4. The measurements on coffee plantations did not include soil sampling in all coffee plants where N_2O was measured. Seasonal water infiltration, water content, and evapotranspiration rates were also not measured. As a result, the estimated values used to comprehend the behavior and how to implement a methodology were inferred from coffee plant scientific literature.

5. This thesis did not cover carbon, nitrogen, nitrification, or denitrification processes.

6. The socioeconomic and bioeconomic conditions have not been studied in depth within the scope of this thesis. However, they are critical for future success and overcoming the intensification of intensive agriculture.

6.7. Recommendations

Some suggestions regarding the composting process are to roof the composting area so that the temperature and radiation do not dry out or affect the composition of the material, mainly during the dry or summer season. In addition, the pulp can have the process undercover and not against the concerns of pathogen vectors, allowing compost all over the year without season limitation.

It is suggested to explore the responses of heterotrophic denitrifiers and nitrifiers in the soil with fertilization and soil amendments. Having knowledge of the soil habitat and how it can affect the responses to the fertilizer applied would give a better understanding of the emissions in coffee plantations (Conen et al., 2002; Norton & Ouyang, 2019). The chamber method often misses hot spots due to the heterogeneous soil properties, bacteria activity, and, most importantly, the fertilizer addition around the plant. Even if some studies recommend the Eddy covariance method to measure continuous fluxes, this would not be a recommendation from the geographical point of view and the amount of plot scale numbers.

One of the recommendations is to use a high-precision device and portable design. For example, the LI-7820 multiplexer system might assess spatial and temporal variability and flux patterns for weeks or months, giving a good option for N_2O measurements on coffee plantations (LICOR, 2022). Another option could be to use a robot system that can carry chambers to take samples at specific times. Robots can cover more comprehensive ranges even though one of the practical issues could be the costs of the systems (Vaidya et al., 2021).

The basis for measuring N_2O emissions is recommended to be measured primarily in unfertilized soils. However, due to the constant increase in agricultural use and the multiple uses of fertilizers to generate the desired yield per crop, no plots were free of fertilizer to perform the baseline. Therefore, it is recommended that measurements be made on organic soils to find a more exact relationship between emissions and chemical fertilizers over time.

Further, explore soil properties and other climatic variables to explain soil emissions' fluxes. Some researchers see emissions as a dynamic process. Here, processes such as nitrification N mineralization, for example, are affected during fertilization (Carpenter-Boggs et al., 2000; Wyngaard et al., 2018). Nitrification and denitrification will be essential processes to monitor in future research. The main suggestion would be to find the relationship of the emissions with the microbiological part of the soil and its mechanisms for production emissions.

It is suggested to improve the understanding and analysis of how microbial activity reacts to the fertilization response. More importantly, during rainy periods and the season and immediately after each fertilization event. However, one of the crucial factors to consider for future assessments is the time between fertilizer application and plant N demand to finalize soil N availability and emissions in agriculture. As soil temperature and humidity vary during each season in Costa Rica in summer and winter, it is advisable to study porosity and microbial activity that influence the chemical reactions, the flow of microbial metabolic activity, and the diffusion these may have through water and porosity.

7. Synthesis, conclusions, and outlook

7.1. Synthesis

Coffee is the second most important agricultural product in value and volume traded internationally. Nearly 11 million ha of land is devoted to its green coffee production, Latin America with 57,6 %, the biggest production region, and Costa Rica holds at least 3% of its territory for coffee production. In Costa Rica, crops and the processing of coffee beans are responsible for at least a quarter of total GHG emissions from agriculture. The main key sources are organic waste from production, honey water treatment, water consumption, and the chemicals used to fertilize the soils.

Climate change and its global and local impacts have generated actions by the coffee sector focused on mitigating those emissions. The research work in Costa Rica was located in the Los Santos region, which is well known for its coffee production, holding at least 30% of the coffee production in the country. According to the most recent ICAFE count in 2022, Costa Rica processed 1,916.959 fanegas. CoopeTarrazú R.L. produced 320.00 fanegas from this quantity, and up to 37,000 tons of coffee pulp have been collected annually.

The soils in the Los Santos Region are classified as ultisols, characterized by low levels of organic matter, and lacking minerals like Ca, Zn, Mg, and B. Furthermore, the high slopes where the coffee is cultivated are subject to erosion and leaching of nutrients, compounded by the exploitation of the soil over 50 or 100 years of continuous cultivation. Out of 37,000 tons of coffee by-products, 1.187 tons were used for this study, which was dependent on the availability of GW, sawdust, ashes, among other materials, to be used in the trials. Currently, the mill is composting to minimize these residues' environmental impacts when they are not treated. Therefore, coffee by-products management, soil fertility and emissions research receive high priority in the mill, and research on organic sources of nutrients must be encouraged and strengthened.

The research questions posed at the beginning of this dissertation are related to creating an innovative methodology for the sustainable management of coffee by-products for the creation of soil amendments. These questions include whether recycling coffee by-products is a viable option for reducing climate-relevant emissions during the coffee production cycle (pre harvest and post-harvest), such as methane and nitrous oxide emissions.

In this context, sustainable management refers to the implementation of new alternatives in Costa Rica for managing coffee by-products derived from primary coffee processing. This allows the linear economy to be transformed into a bio-economy or circular economy. As a result of this, a product like compost is obtained in such an important agro-industrial sector in order to obtain a low-cost alternative for farmers as a soil amendment. This meant that during this development, the needs of the present were taken into account without compromising future generations' ability to meet their own needs at the Mill.

To answer the thesis questions, various trials were carried out at various phases of the composting process and fertilization on coffee farms in the Costa Rican mill. To assess the effectiveness of the composting process for the management of coffee by-products, key composting parameters, including water content, pH, C/N ratio, aeration of the pile, and temperature, were monitored. This allowed researchers to identify the variables influencing the composting of coffee pulp and identify potential improvements. In addition, for the performance on coffee plantations, the N_2O emissions during fertilization during a particular time of the year, employing various synthetic fertilizers and soil additives, were observed.

In order to close knowledge gaps in emissions reduction and the sustainable management of coffee by-products for use in coffee farms in the future and to develop a valuable product as a result, outcomes that were supported by evidence were acquired for each research topic.

Research results were in three peer-reviewed articles, and each paper presented a clear and succinct explanation of the findings and an in-depth discussion of the key findings. The results of the dissertation are outlined in the following sections, which also cover emissions rates during the composting process when adding various amounts of coffee pulp and green waste, the composting of coffee by-products, and the behavior of N_2O emission rates during the application of various types of synthetic fertilizers (physical and chemical) to coffee plantations and in various varieties of coffee (Catuai and Geisha).

The main finding of the dissertation was proof that coffee pulp is an acceptable substitute for composting when green waste is included, and their CH_4 emission can be decreased by up to 93%, leading to a considerable decrease in emissions compared to the initial state of the mill. Moreover, the N_2O from the fertilizers varied depending on the year's season, rainfall, and type of SNF used.

Based on the current situation, figure 7 - 1 describes how the thesis evolved and why it is important to use the methodology proposed. There was no data on CH_4 emissions during composting with coffee pulp, and the essential parameters to ensure were not monitored weekly.

As a result, the goals of this thesis were important: collect data, calculate emission rates, and train personnel for future composting processes at the mill following composting key parameters. Concerning crop plantation, no emissions in the mill's crops were previously measured.

With the proposed thesis, N_2O emissions related to the type of fertilizer (inorganic fertilizers of physical and chemical composition) and soil amendment were quantified, obtaining emission rates indicated as in $g \times m^{-2} \times h^{-1}$. More over carbon footprint in CO_{2e} kg^{-1} green coffee were calculated during composting and fertilization.

One of the most important organic materials that can easily be used as soil amendments for coffee plantations is coffee pulp, a by-product of wet processing once the coffee cherry is harvested. Essential quantities of such by-products are generated annually and disposed of without proper utilization. Converting these by-products for soil amendment requires decomposing them through composting.

One of the biggest challenges the stakeholders face during each harvest is the cost-effective management of the coffee by-products, especially the coffee pulp, since it comprehends more than 29% of the dry weight of the coffee cherry. When it is left for natural degradation, it may take eight months to years to stabilize the organic matter, indicating anaerobic conditions and methane emissions.

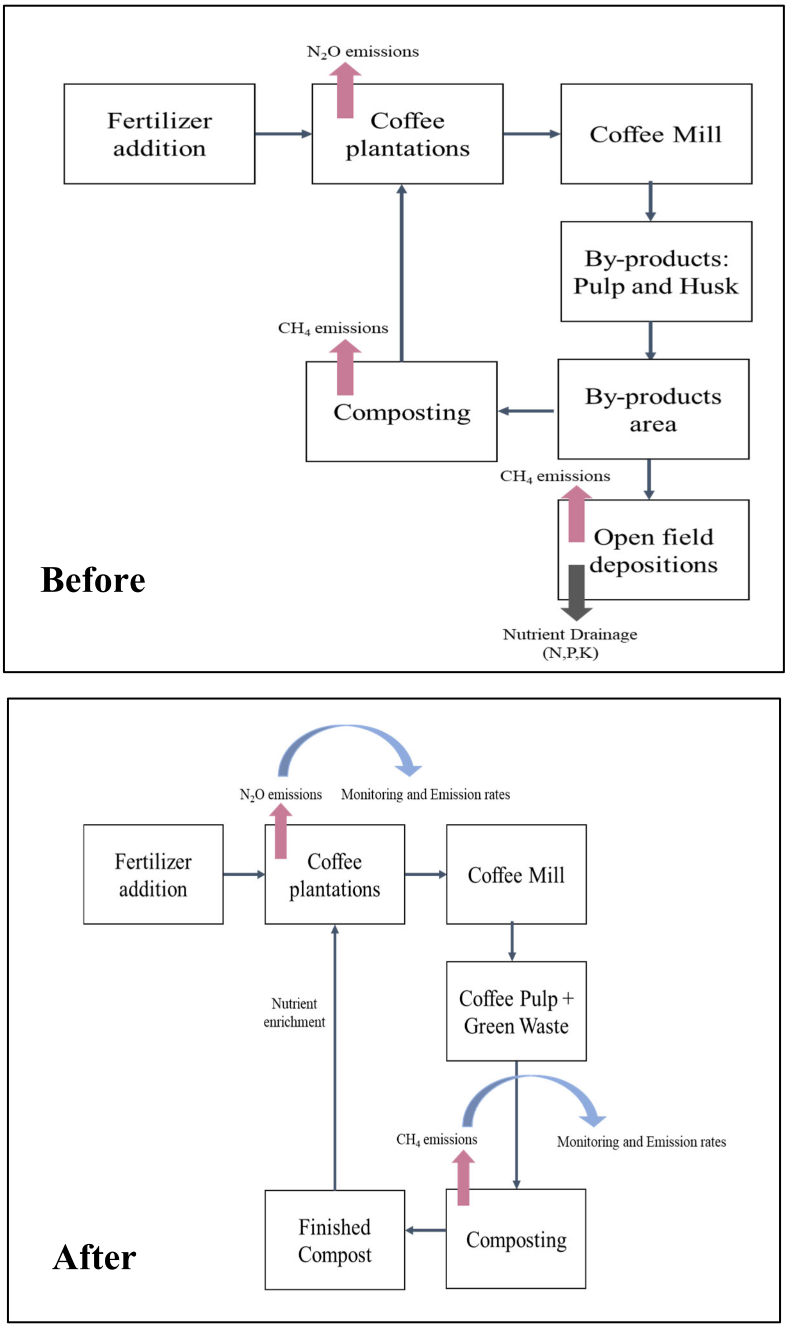

Figure 7 - 1: Summary of the thesis proposal, including how the current status in the mill, the development during the study, including the addition of green waste materials, composting, and emissions measurements.

Regarding composting parameters as a sign of process stability and maturity, the proposed treatments achieved a dark brown color, odor similar to soil, ambient temperature and consistency after turning, pH lower than the mill's actual treatment (between 7 - 8), a C/N ratio less than 22, a seed germination index greater than 80%, and bulk density between 400 - 500 g/L.

All of the parameters obtained were within the author's recommended range for indicating a proper composting process (Azim et al., 2018; Cornell University, 2001; P.Bueno, R. Tapias, F. López, 2007). During the composting weeks, measurements revealed that adding GW, has significant benefits.

Even though the effectiveness and results of all the different GW and CP mixture ratios showed to have a favorable impact on the nutrient content. One of the GW mixtures with percentages of 20%, 30%, 40%, and 50% achieved exceptional results for levels of N, NO_3^-, and Mg^{+2}. Therefore, adding 40% of the mixture's volume of GW results in the best mixture for use as a soil amendment that satisfies the recommendations for the type of soil on coffee plantations in terms of nutrient content.

When GW was added to compost piles, CH_4 emissions were reduced by up to 89% when 40% of the mixture volume was used, and by up to 93% when 50% of the mixture volume was evaluated. As a result, emissions that were climate-relevant and occurred before the application of this methodology suggest mitigation measures that would support the continuation of these environmentally sustainable and economically advantageous processes for managing coffee pulp with low or negligible emissions.

Coffee pulp composting requires a small capital investment and, in less time, produces a high-quality soil amendment than natural stabilization (Dawid, 2018). Compost from coffee processing, primarily coffee pulp, can be used successfully as an organic fertilizer for coffee production. The use of coffee pulp compost significantly improved the growth and yield of mature coffees, according to some studies (Chong & Dumas, 2012b; Kassa et al., 2012).

One of the leading causes of global warming in agriculture is nitrogen volatilization, with a global warming potential of 200-fold compared to CO_2. Estimating 0.1 and 1% of the nitrogen utilized in fertilizer volatilizes as N_2O (J. Luo et al., 2007). For instance, 240 to 300 kg of N, 80 kg of P, and 240 to 260 kg of K per hectare per year are required if a coffee crop yields 20 fanegas of parchment coffee per hectare per year.

Contrarily, fertilizers are not necessary for crops that yield five fanegas or less coffee per hectare per year (Capa et al., 2015b; Jensen & Dicks, 2012). To sum up, the amount of fertilizer applied to coffee relies on the potential yield, the number of plants planted per hectare, and the findings of the soil analysis, which show how much nutrient is present in the soil for each hectare of crop. In Costa Rica, the SNF total amount added in coffee plantations suggested by ICAFE in kg x ha^{-1} x y^{-1} is 205 - 287 of N, 20 of P, and 150 of K.

Higher fertilizer prices add to the strain of rising agricultural material costs, tugging farmers as food inflation reaches new highs. Costa Rica's coffee industry is scrutinizing soil content in the main producing regions in hopes of reducing the need to apply nutrients to the ground, according to ICAFE.

It usually is needed in some coffee farms, around 1,400 tons of fertilizer to produce about 40,000 bags (approximately 46 kg each bag) of coffee each year. However, the price for the formulas used as fertilized has tripled since last year. Therefore, growers are diluting nutrients to stretch scarce supplies where the prices from 2021 to 2022 increased up to 152 percent for every bag of fertilizer. Therefore, it is of great importance to search for alternatives giving waste valorization from the same coffee production and harvest to recover soil properties and to help minimize the impact not just related to climate change but also on the future economy of the coffee growers.

Regarding the emissions, the measurements were made using chambers, having the advantage of simplicity and economy. It has been found in the literature to be a reliable method for terminating emission ranges in compost piles and soil (Bertora et al., 2018; Pihlatie et al., 2013). In the case of coffee plantations, the use of chambers in conjunction with FTIR enabled continuous real-time measurements, particularly to assess N_2O fluxes from the soil in the field, with less frequent calibration required.

The N_2O flux measurements reported in this thesis were made using a dynamic, open chamber. The dynamic chamber method was developed to improve soil's precision of N_2O flux measurement. The dynamic chamber has been used at various field sites run by different research groups worldwide for N_2O measurements and soil fluxes. For security and fauna reasons, all measurements were taken during the day, including the rainy and dry seasons of the coffee production cycle. The outline of the results chain presented in this thesis is shown in Tables 7 - 1 and 7 - 2.

To summarize, the variables influencing emissions that were taken into account for the data provided in this thesis and for future inventories were related to i) climate (wet or dry), ii) management practices such as time of addition of the fertilizer, iii) land cover, and water management, iv) edaphic properties in the topsoil and v) soil alkalinity.

Table 7 - 1: Overview of the thesis results related to composting.

Criteria	Initial state	Result of the research work
Composting		
Experimental methodology development and CH_4 emissions and key composting parameters control	No waste valorization High emissions Daily Mechanical Turning	Circular economy Low emissions Weekly Mechanical Turning
Inputs	Coffee pulp + husk	Coffee pulp + green waste Green waste is suggested at different percentages in mixed ratios (from 50% to 80% mixture).
Turning	Daily	Weekly
Monitoring of key parameters	No	Yes
Pathogens	High	Low
Emission rates average in the field (Costa Rica) in $g \times m^{-2} \times h^{-1}$	21.86	1.79
Fumigation	Weekly	None
Soil amendment	Unfinished compost	Finished Compost
Summary	• Nutrient drainage. • Avoidable CH_4 emissions. • Environmental pollution. • No monitoring of CH_4 emissions. • Incomplete handling of coffee by-products, resulting in CH_4 emissions and nutrient loss.	• Nutrient cycling, CH_4 emissions reduction. • Nutrient enrichment all contributes to increased soil fertility and drought resistance. • Composting improvement and CH_4 reduction after the addition of green waste. • Emission rates during composting. • Compost should be applied during the dry season due to the ease of management in areas in the middle of coffee plantations.

Table 7 - 2: Overview of the thesis results related to Coffee plantations.

Coffee plantations		
Criteria	**Before measurements**	**After measurements**
N_2O emissions and set-up for on-site measurements.	In the country, no studies using the proposed technique have been reported. There is little information on N_2O emissions or fertilization practices.	FTIR measurements technique proposed. Emissions Fluxes in different varieties of coffee and types of synthetic fertilizers.
N_2O measurements	No	Yes
Field trials were conducted to investigate the impact of coffee by-products as a soil amendment in coffee plantations.	No data on N_2O emissions and soil amendment behavior once coffee plantations are added.	Soil amended resulted in the lowest N_2O emissions presented in the study.
N_2O emission rates average $g \times m^{-2} \times h^{-1}$ with different types of fertilizer	No data in the country	0.04: Soil amendment 2.65: Physical 0.54: Chemical 0.30: Control
Soil amendment	Unfinished compost	Finished Compost
Summary	• Environmental pollution. • No monitoring of N_2O emissions	• Emission rates during fertilization. • Physical fertilizer has higher emissions than chemical fertilizer.

7.2. Conclusions

The thesis developed an experimental methodology using coffee by-products and green waste materials. Key parameters were improved with the proposed composting process, and the valorization of waste within the process and reducing methane emissions were successful. This methodology achieved low emissions during the coffee waste management and finished compost classified (Grade IV and V). Future use will correspond to what the mill deems convenient to use. However, the suggestion is to use at least 30% green waste and bulking materials for composting.

It was found that CH_4 emissions could be avoided if the mixing and formation of the piles were carried out following the key parameter for composting. With this, the coffee sector will improve the management of coffee by-products during the harvest season, obtaining a product with low emissions to be used later in the coffee plantations as an amendment to their soils. Therefore, emission factors are directly linked to the management made in the mill. When the pulp is composted without any bulking materials and green waste, the highest emission factor is presented, such as 129 g CH_4 / kg CP with 100% coffee pulp in the compost pile. In contrast to 22.6 g CH_4 / kg CP as an average, when the composting pile is a mixture of green waste and coffee pulp. Moreover, when the pulp has been buried for more than two years, 1.684 g CH_4/ kg green coffee can be emitted for many years in the field depositions.

The optimal value obtained in terms of emissions was when the coffee pulp was composted with green waste at 50% mixture volume giving values of 11.6 g CH_4 / kg CP. Therefore, composts made from coffee pulp combined with green waste are suggested to increase coffee yield in the future significantly. It can thus provide much of the mineral nutrients required by the coffee tree for average growth and sustained yield and enable the production of organic coffee, which is currently in high demand worldwide. In terms of carbon footprint, composting released an average of 0.04 kg CO_{2e} kg^{-1} green coffee when GW is used, compared to 0.4 CO_{2e} kg^{-1} green coffee for the control treatment. Furthermore, field deposition can contribute 2.1 kg CO_{2e} kg^{-1} green coffee.

Above all, these practices are both environmentally friendly and cost-effective. Composting coffee pulp and green waste materials accelerated the composting process and improved nutrient balance. Integrated nutrient management through organic and inorganic sources, as well as agro-forestry prunes and trees, must be evaluated in the country's various coffee production systems and agro-ecologies. The soil amendment proposed in this research is higher quality than that previously applied to coffee plantations. The soil amendment obtained has higher boron, zinc, and organic matter content. As a result, the fertilizer obtained is much richer, allowing it to improve soil structure without acidifying it. It is an excellent benefit for farmers, as it can help coffee soils and increase productivity in the area.

At the level of N_2O in coffee plantations, this thesis attempted to estimate punctual fluxes among coffee production cycles. The methodology was successfully tested and implemented on coffee plantations in Costa Rica, testing two types of coffee varieties at different months of the year. It was concluded that rainfall impacts the emissions, especially when fertilizer is added and rainfall occurs. The effect of rainfall on emission events might be linked to nitrogen availability in the soil; nevertheless, deep research is suggested to conclude this statement. Although rainfall was present during a good part of the evaluation period, it seems to influence only after applying fertilizers. The highest emissions reported were after one month of fertilizer application, with N_2O–N rates between 0.1 – 0.25 g x m^{-2} x h^{-1}.

Moreover, after rain events, it was seen that the emissions rates increased, having a link between water in the soil and fertilization, obtaining an increase in N_2O emission rates between 0.3 g x m^{-2} x h^{-1} – 0.5 g x m^{-2} x h^{-1}. Thus, inorganic fertilizers produce more N_2O emissions depending on the time of application, and one variety of coffee slightly contributes more emissions than another (Catuai higher than Geisha variety). This phenomenon might be linked to the properties of the soil and the uptake of nutrients from the plants.

The results of this thesis will be a helpful tool for future calculations of global emissions in the coffee sector using a technology already studied at the mill. Moreover, the thesis covered several important climates and environmental issues to consider, especially quantifying the coffee sector's emissions, giving data for further mitigations and waste treatment with low emissions for a nutrient-rich soil amendment. Furthermore, this helps promote regenerative agriculture, strengthens soil fertility, and mainly increases microbiological, mineral, and organic matter presence. It is believed that increasing amounts of SNFfs are required to achieve a moderately acceptable level of agricultural production. Poor agricultural practices have destroyed the soil's biological, physical, and chemical balance. In addition to the energy and environmental costs of chemical fertilizer production, the environmental and economic costs of applying these fertilizers to crops must be considered.

The farms in Costa Rica, mainly the mill where the study was conducted, aiming to reduce the use of SNF and gradually reduce reliance on these SNF products. The proposal in this thesis addressed the specific needs of farmers by addressing key strategic metrics for sustainable management of coffee by-products, which included environmental, economic, commercial, and social concerns. As a result, new production processes have been developed that allow the organic matter generated during the industrialized processing of the coffee fruit to obtain a waste valorization and even suggest a circular economy model in the mill. With this, the challenges meet the needs of coffee producers while also contributing a more affordable alternative instead of SNF. Composting is thus thought to be a feasible and low-cost technology for dealing with by-products of coffee processing to be used in coffee plantations for N_2O emissions reduction and soil amendment. Furthermore, the project supports Costa Rican public policy to decarbonize the economy. Using biomass available in the agricultural sector supports the national Bioeconomic strategy and the UN Sustainable Development Goals. With rising demand and numerous sustainability challenges in traditional coffee agriculture, there is an urgent need for alternative coffee production methods.

The evaluation of N_2O emissions is critical for implementing climate-responsive actions such as limiting GHG emissions from cropping fields, limiting the use of SNF fertilizers, and testing alternative soil nutrient enrichment methods. At least half of our current carbon dioxide dilemma comes from unsustainable agricultural practices, which is why change is in our hands. Healthy soil equals quality coffee, strengthening supply chains and prosperous farmers (Letcher, 2020; Nyong & Martin, 2019).

7.3. Outlook

This thesis focuses on an upper-middle-income country, such as Costa Rica. However, these findings may support the larger-scale implementation of various business models or initiatives for low- and middle-income countries and industrialized countries. This thesis attempts to broaden the utilization limits of available coffee by-products, connect technological possibilities with systemic grid requirements, and contribute to the sustainable management of coffee by-product provision that is useful in agriculture, economically viable, and environmentally friendly.

The suggestion of using an appropriate-technology thermophilic composting effectively minimizes CH_4 emissions and nutrient loss, producing a stable compost rich in nutrients. This technique was an approach to sustainable management of coffee by-products that may contribute to climate change mitigation, nutrient retention, and decrease the dependency on SNF in the future. It may further contribute to climate change mitigation by reducing GHG emissions during coffee waste management in agricultural ecosystems and coffee plantations. It also improves soil health, harvest security, and water quality by enhancing nutrients and water retention. Our findings have important implications for the future of sustainable recycling of coffee by-products and their further reuse to improve soil fertility and agricultural productivity, particularly in areas with financial and infrastructural limitations.

Moreover, the obtention of CH_4 emission rates during composting and N_2O during fertilization in coffee plantations were studied. Recognizing the value of coffee by-products, particularly coffee pulp and other organic waste reuse-based businesses, can completely reinvent the coffee industry and agriculture's economics. This work addressed all of the objectives and its research questions. However, given the implications of this approach or other initiatives that also seek to close the plant's nutrient cycle, some gaps remained to ensure the success of these sustainable coffee by-products/coffee waste management/agriculture strategies successful:

i. Further research on coffee pulp: There is a spectrum of different applications where, depending on the demand and the feasibility of the country, it could be decided to use the coffee pulp for different purposes, even though during the thesis, research questions regarding the constituents and physical chemistry properties of the coffee by-products and its behavior during the composting process were addressed.

The Costa Rican mill decided to employ composting because of the amount of residue produced by each harvest, particularly to assist its farmers and plantations by providing them with a soil amendment. It is important to consider the needs of the farmers, especially when there are more than 5.000 tons of residue per harvest, such as climate, infrastructure, and time are factors in the future usage of the by-products. That is why it is recommended, based on the results, to apply composting treatment for sustainable management of coffee by-products. However, there are only a few studies in the scientific literature investigating the efficiency and the key parameters of composting using coffee by-products and using the soil as an amendment.

ii. Further research in the agro-industrial sector in Costa Rica: There are still significant knowledge gaps about composting process enhancements in monocultures, such as when a homogeneous material is considered a residue. According to the current literature search, there is little research on compost production from agro-industrial waste, especially at the semi-industrial or commercial scale. Composting in large-scale production is difficult to control compared to small or laboratory-scale production because it is a self-heating process that hinders the process's replicability or reproducibility.

More research on the stability, kinetics, and mixtures of other bulking materials and green waste is suggested. A scale of semi-industrial or commercial is needed for different composting systems, from the aerated static pile to the in-vessel system, to validate the repeatability and benefits reported in small-scale studies. Research in modeling and optimization for all composting systems using the engineering processing technique would be required to enhance the process without compromising the quality of the composting product. Studies on significant statistical correlations between composting and emissions and important factors such as moisture content, temperature, oxygen in a pile, and pH at different composting stages should be conducted to monitor the process.

iii. Measurement, reporting, and verification (MRV), long-term trials, and indicators: There are currently emissions at farms and mills related to green coffee. However, there is no robust MRV framework to measure, report and verify emissions from types of SNF used on coffee plantations. By doing so, emissions could be tracked at the country level, helping to monitor the environmental impact throughout the process. Research questions arose during the thesis, especially developing a methodology for quantifying N_2O on coffee plantations. Nevertheless, field trials over several crop seasons are required to evaluate the long-term effect of coffee pulp compost, especially of large application amounts, on soil fertility and crop performance.

iv. Regulations, technology transfer, and information among the population and coffee growers: It is crucial for research to be successful in transferring all of the knowledge acquired so that it can be used further in the mill when creating new laws and stringent regulations regarding what takes place in the farms during the coffee cycle (harvest and growing).

For instance, it was challenging to compare the final optimization of the thesis since the country had emission rates or emission factors related to the amount of fertilizer and composting on coffee pulp. Therefore, restrictions and new composting regulations on using this material for agricultural purposes should be re-evaluated.

Clear policies need to be developed to ensure the safety and quality assurance of the production and use of coffee by-products as soil amendments in the country. Governmental support could help enhance research, knowledge, awareness, and social acceptance and thereby overcome perceived barriers to using nutrients from the coffee pulp. Moreover, in Costa Rica, producers bet that their soil holds enough lingering nutrients to carry them through the next planting season. Some consider organic waste a cheap substitute for N, P, and K fertilizers.

In terms of mitigation, consumers prefer companies to change technology, and using more sustainable technology is seen as an added value to products. Therefore, in parallel with the mill personnel, technology transfer, research, and innovation are necessary steps toward success for future implementations. As an added value to products, the use of more sustainable technology is needed.

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Appendix

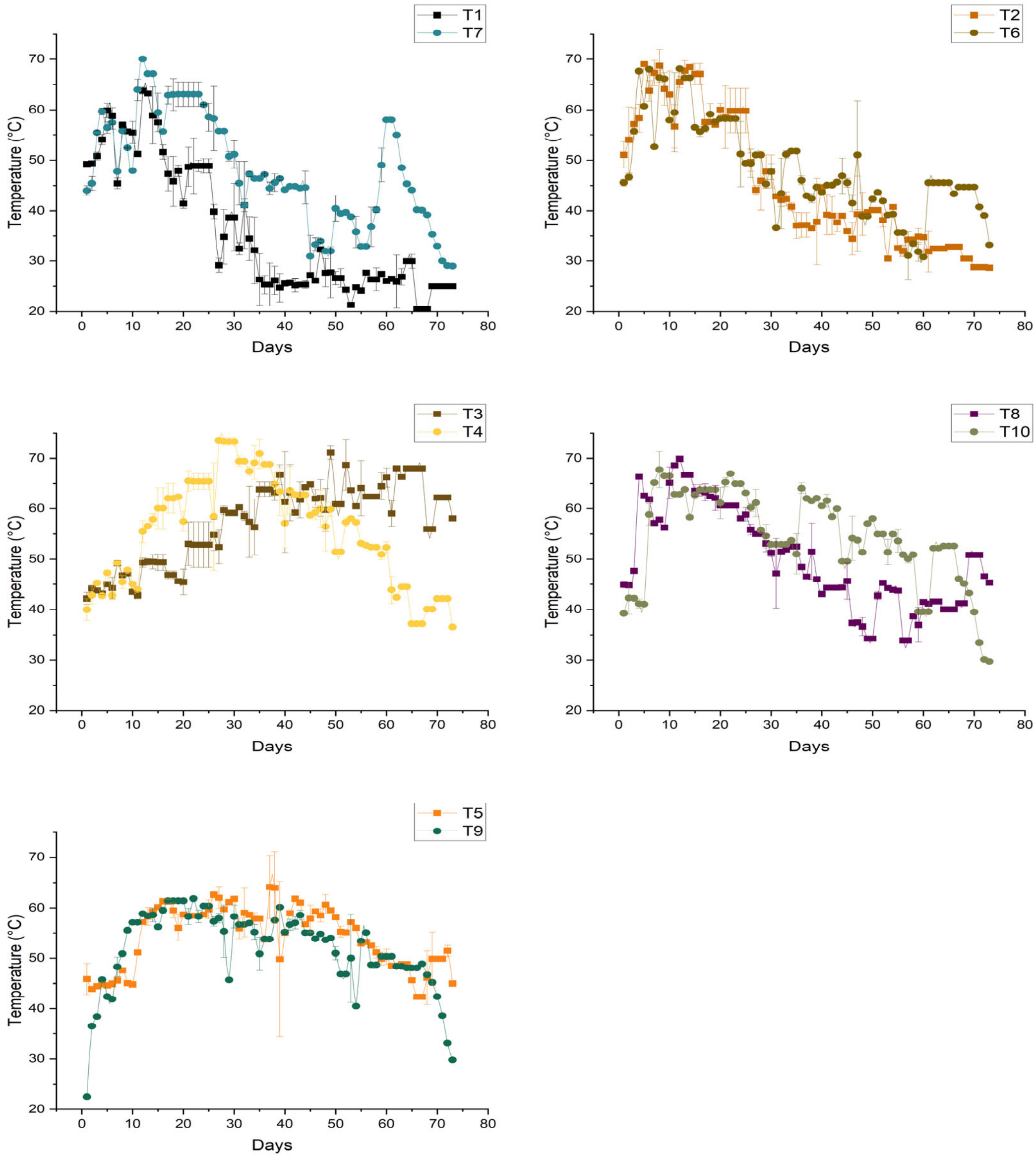
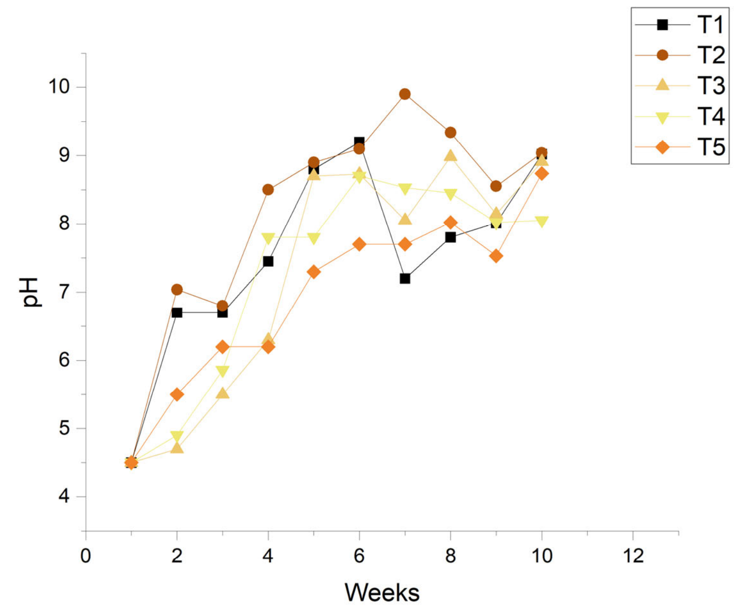


Fig Ap 1. Temperature profiles with all the proposed mixtures in the second stage of the study in the harvest 2018-2019. The figures show the typical development of composting processes containing self-heating, cooling, and stabilization. The turning of the material caused low peaks, reflected in the graphs. T1: 60% pulp - 40% GW; T2: 50% pulp - 40% GW- 30% GW - 20% processed pulp; T3 Blank : 100% pulp; T4: 85% pulp -15% husks, T5 33,3% pulp - 33,3% sawdust - 33,3% processed pulp; T6: T1 under roof; T7: T2 under roof; T8 40% pulp -15% pore - 20% green organic material - 20% processed pulp - 5% ash; T9: T5 under roof.

Appendix



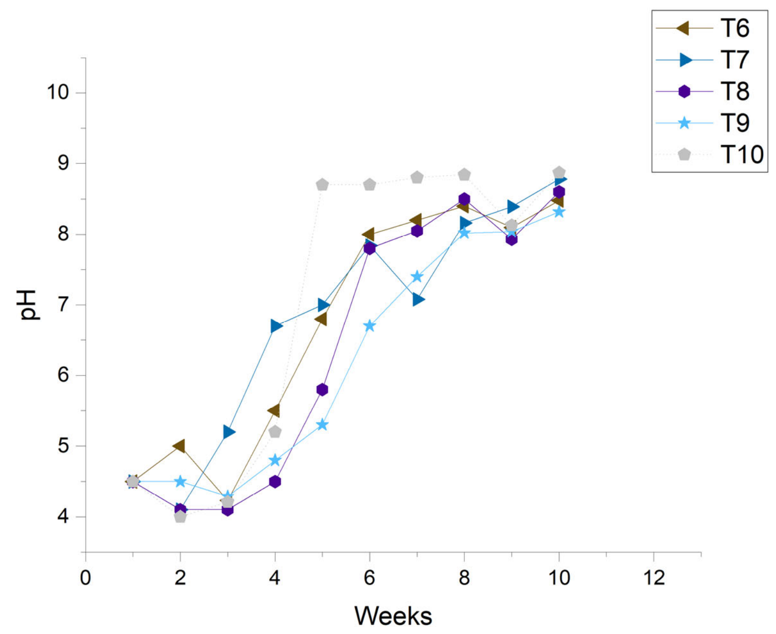


Fig Ap 2. The pH and WC profiles with all the proposed mixtures in the second stage of the study in the harvest 2018-2019. T1: 60% pulp - 40% GW; T2: 50% pulp - 40% GW- 30% GW - 20% processed pulp; T3 Blank : 100% pulp; T4: 85% pulp -15% husks, T5 33,3% pulp - 33,3% sawdust - 33,3% processed pulp; T6: T1 under roof; T7: T2 under roof; T8 40% pulp -15% pore - 20% green organic material - 20% processed pulp - 5% ash; T9: T5 under roof; T10: 50% pulp- 20% GW -10% sawdust - 20% processed pulp.

Fig Ap 3. Buried Pulp. This image depicts what the pulp looks like after being buried during the 2017-2018 harvest and de-stemmed (about 40 cm deep) in 2020. It can be seen how the pulp looks at the end as if that were fresh.

Fig Ap 4. Loss in volume after two weeks of composting process during harvest 2019-2020. Part A depicts the composting piles at the start of the process, while Part B depicts the piles with volume loss (a shade in the floor of the piles can be seen, representing the compacting of the pile and its shrinkage).

Fig Ap 5. Beans Bioassay with the proposed treatment in Costa Rica made in 2019-2020 using the compost proposed during the project, the current treatment of the mill, and control using soil from the mountains.

Fig Ap 6. Beans Bioassay with the proposed treatment in Costa Rica made in 2019-2020. Roots difference between the control, the current treatment of the mill, and the proposed compost material (DE).

Fig Ap 7. Bioassay laboratory scale with beans 35 days made at the ISWA Institute, Germany, to test the differences in percentage ratio of mixture and type of compost shipped from Costa Rica with the different treatments proposed in the project.

Fig Ap 8. Green Waste is suggested for collection in the mill for the future continuity of the proposed treatment at the mill. The suggestions include green waste and structural materials from the surroundings of the mill, cuttings of trees, pruning of the coffee plants, and any organic structural material available to be composted.

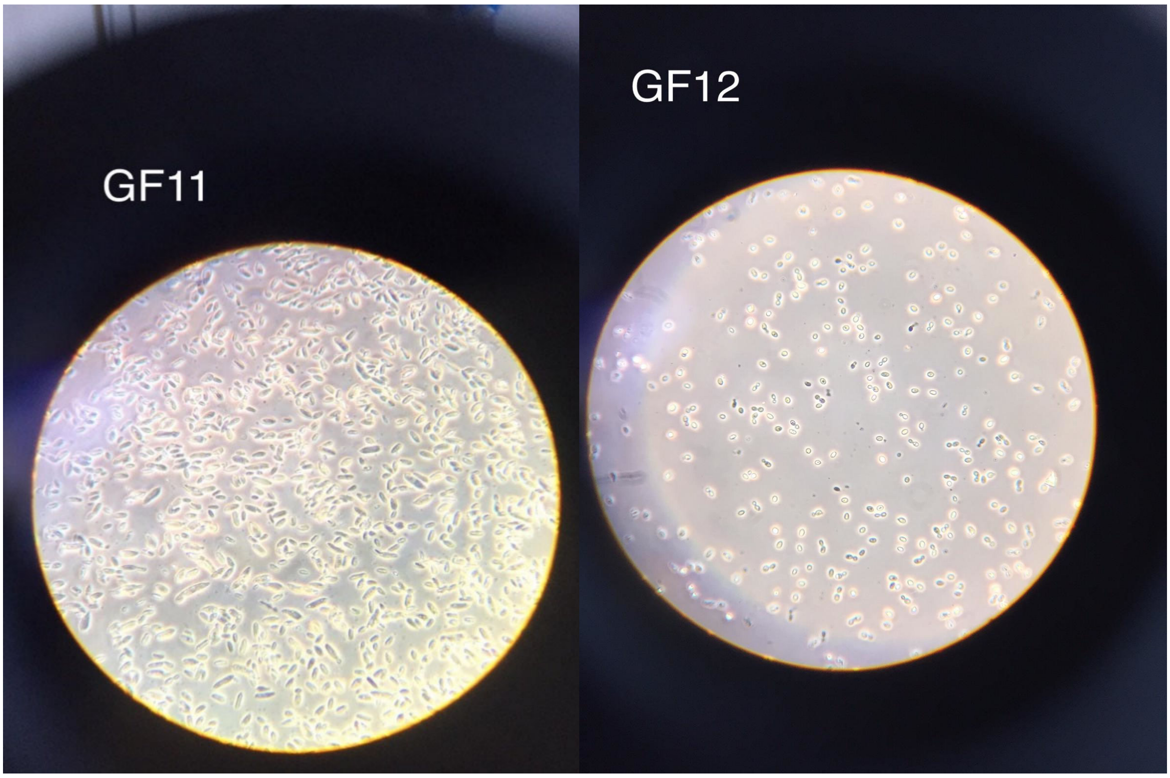


Fig Ap 9. Two images under the microscope of the fungal activity present in two weeks of the composting process. GF11: a mixture of coffee pulp and green waste. GF12: 100% coffee pulp. The figure represents a sample under the same dilution, but different colonies for the composting process carried out with the mixture of coffee pulp, green material, and structural material. In addition, a bacterial study was conducted concurrently with the research to identify the bacteria in the coffee pulp and the mixture of coffee pulp with structural and green material. The concept was based on identifying the types of bacteria and fungi present in both processes, the amount of oxygen required by the microorganisms, associated enzymatic activities, and colony counts, among other things. Significant differences were found at the bacterial and fungal levels, indicating that the mixture of materials has higher biological activity than when the composting process is carried out homogeneously using only coffee pulp as substrate.

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Conferences and presentations:

IV International WASTE Symposium: Current Challenges in Sustainability, Virtual Conference, 4-5th November 2021.

Tropentag: Towards shifting paradigms in agriculture for a healthy and sustainable future. University of Hohenheim, 15-17th September 2021.

Nature conferences: Sustainable Solutions for Pollution Control. Virtual conference 28th April 2021.

Tropentag: International Research on Food Security, Natural Resource Management and Rural Development, Virtual conference. 9-11th September,2020.

III International WASTE Symposium: Environmental and process engineering and technologies, Stuttgart, Germany 8th November 2019.

7th International Conference on Sustainable Solid Waste Management, Crete, Greece, 2019.

Wissenschaftskongress Abfall- und Ressourcenwirtschaft, Amberg, Germany, 14.-15th March 2019.

II International Waste Symposium, Stuttgart Germany 3rd November2018.

Declaration of independence

I declare with my signature that I have written this thesis on my own and that I have used no other than the stated sources. All passages of this thesis, which are taken from other works, the sense or the argumentation are taken from other works (including the World Wide Web and other electronic text and data collections), I have fully acknowledged the sources.

Zurich, 16.06.2023 Macarena San Martin Ruiz

Place, Date Signature

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