Ground Zero? Let's Get Real on Regeneration!

Report: Assessing greenhouse gas emissions from post-harvest residue management in coffee and cocoa production systems

G0 Ground Zero

Colophon

Ground Zero? Let’s Get Real on Regeneration! is a collaboration of Wageningen University & Research (WUR), Nestlé Research, Olam Food Ingredients (Ofi), OneCGIAR, ETH Zurich and various partners across the tropics

Lead authors:
Késia Silva Lourenço[1]

With contributions from:
Matti Barthel[2], Gerard Velthof[3], Dorien Westerik[3,4], Eric Rahn[5], Mirjam Pulleman[4,5], Johan Six[2], and Ken E. Giller[1]

[1] Plant Production Systems, Wageningen University & Research, Wageningen, The Netherlands
[2] Sustainable Agroecosystems Group, Department of Environmental Systems Science, ETH Zurich, Switzerland
[3] Wageningen Environmental Research, Wageningen University & Research, Wageningen, The Netherlands
[4] Soil Biology Group, Wageningen University & Research, Wageningen, The Netherlands
[5] International Center for Tropical Agriculture (CIAT), Cali, Colombia

Authors’ contributions:
KSL wrote the report. MP, GV, MB, JS, ER, DW and KEG provided critical reviews and suggestions.

Please cite this report as:
Lourenço, K.S. (2024). Assessing greenhouse gas emissions from post-harvest residue management in coffee and cocoa production systems. Wageningen University & Research, Wageningen. pp. 46 including annexes. DOI: 10.18174/661314

DOI:
https://doi.org/10.18174/661314

Graphics and design
Késia S. Lourenço

Acknowledgements

The Ground Zero project is led by Wageningen University and Research and funded through the Nestlé Institute of Agricultural Science.

A large number of experts were consulted during the development of the report to whom we are most grateful. We hope we have not overlooked any in the list below and apologise in advance for our oversight if we have.

In particular, we thank Piet van Asten (OFI) for his insights related to coffee production worldwide, especially about the residues generated during the coffee production process. We are grateful for the discussion with Felipe Santinato about coffee production in Brazil.

We thank Marieke Sassen, the leader of the Ground Zero project at Wageningen University and Research, for all her support and expertise. We also thank Andrea Diaz for all her support and for revising the final version of the report.

We thank Catherine Neyret, Hubert Coffi, Miguel-Angel Lopez Murcia, and Namy Espinoza Orias of the Nestlé Institute of Agricultural Science for their critical review and comments on earlier drafts that helped improve the report

Contents

Executive Summary

The critical need for the world to confront climate change has prompted major food industry players to make ambitious pledges to reduce greenhouse gas (GHG) emissions. Considering that a significant portion of GHG emissions within supply chains arise during the production of agricultural commodities, attention has now shifted towards "Regenerative Agriculture" as a pivotal strategy to reducing the carbon (C) footprint, alongside enhancing soil health and safeguarding biodiversity, while ensuring sustainable production and providing living incomes for farmers.

The production processes of coffee and cocoa are intricate and multifaceted, yielding not only the desired end products but also generating a substantial volume of residues. These residues emerge during various stages of post-harvest processing, encompassing wastewater, coffee husks, cocoa pod husks, pulp, and bean shells. Only in 2022-2023, the production of coffee residues reached about 10 million tonnes of solid waste and around 150 billion litres of wastewater globally. For cocoa, the residue production is estimated to be around 12.4 million tonnes per year. Improper handling of these residues can lead to a range of environmental challenges, including water pollution and eutrophication, K leaching, and the release of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). C footprint calculations (expressed as CO_2-C emission rates per kg of product produced) require the inclusion of the emissions from all activities inside the farm (*on-farm*), including those upstream related to the manufacture of farm inputs (*off-farm)* such as fertilizer and transport of materials to the farm, as well as post-harvest processes down the value chain. Post-harvest processing can occur on-farm or off-farm in centralized processing plants. Therefore, GHGs emitted during post-harvest processing and the treatment of wastewater and residues generated *on-farm* must be considered. By understanding the intricacies of residue generation and exploring the sources of GHG production, stakeholders in these industries can work towards minimizing the ecological footprint in the supply chain and promoting more sustainable production.

In this report, we provide a comprehensive overview of the various residues produced during the processing of coffee and cocoa beans from harvest to green/dried beans, including processing that takes place directly on the farm and at centralised post-harvest processing facilities, such as washing stations in the case of coffee or cooperatives/collection centers in the case of cocoa. We also review the most common residue management strategies farmers use and their environmental implications in terms of GHG emissions, with a focus on CH_4 and N_2O. The primary objective is to identify the main points of environmental concern and propose methods for monitoring CH_4 and N_2O production during solid residue and wastewater treatment.

The most common practice farmers use is leaving solid residues on the farm or centralised facilities in piles without proper management, probably leading to high GHG emissions, especially CH_4. Similarly, in farms/ centralised facilities that use water for processing, wastewater is typically left in ponds without additional treatment. However, limited data is available on the total GHG emissions in such circumstances. Further research is needed to understand the role of emissions from residue piles and wastewater ponds in GHG production and their impact on the overall C footprint of coffee and cocoa production. Considering all the available methods used to measure CH_4 and N_2O emissions, it is proposed to use the static chamber method to quantify GHG emissions from residue piles and the floating chamber method in combination with the headspace equilibration method for wastewater. These methods are relatively inexpensive, easy to adopt, versatile, and adaptable to varying field conditions. Employing these methods enables comparisons of different treatments across various piles and ponds, facilitating the development of strategies to decrease GHG emissions during compost production and wastewater treatment. Studying the entire life cycle of coffee and cocoa industry products, including residue management practices, is crucial for developing sustainable solutions and reducing environmental impact.

1.Background

Coffee (*Coffea* spp.) and cocoa (*Theobroma cacao*) are two important agricultural commodities globally. As the demand for sustainably sourced products increases, the coffee and cocoa industries find themselves at a critical crossroads. The environmental impact of these industries has become a matter of concern, requiring a proactive approach towards addressing challenges such as residue management, water usage, and GHG emissions (Dadi et al., 2019; Campos et al., 2021). The definition and adoption of good agricultural practices and resource-efficient technologies are critical to ensuring the future of these industries while mitigating their potential adverse impacts (San Martin Ruiz et al., 2020; 2021). In this context, the scientific exploration of residue generation and management and its environmental consequences deserves increased attention.

Dried beans are the primary products of interest in the coffee and cocoa industry. However, numerous residues are generated at and after harvest. The post-harvest processing can occur *on-farm* or *off-farm* in centralized processing plants. In coffee production, beans are extracted by removing the outer layers of the coffee cherry, resulting in coffee pulp, mucilage, and wastewater (coffee husk) (Figure 1). In the 2022/23 coffee production season, a total of 10 million tons of coffee beans (168 million bags) were processed worldwide (ICO, December 2023). This resulted in the generation of a significant amount of agricultural residues, accounting for 30% to 100% of the total coffee beans' weight, depending on the processing method (ICO, 2011; Oliveira and Franca, 2015). The International Coffee Council states that green coffee beans represent 50% of the dried coffee cherry (ICO, 2011). This translates into approximately 10 million tonnes of solid residue generated during this period. Additionally, substantial amounts of wastewater are produced. The water consumption for making a washed coffee varies hugely depending on the operations, ranging from 25 to 50 litres per kilogram of coffee beans. Considering that 30% of coffees globally are washed (mainly *Coffee arabica*), 75 to 150 billion litres of wastewater are produced (Oller et al., 2011; Pulleman et al., 2023; ICO, December 2023). Ideally, postharvest processing should utilize less than 10 litres of water per kilogram of dry beans (Pulleman et al., 2023), even so, the amount of wastewater generated would be 30 billion litres. Similarly, in cocoa production, the extraction of cocoa beans leaves behind cocoa pod husks and bean shells (Figure 2). The cocoa industry generates substantial quantities of residues, with nearly 3.3 tons of dry residue produced for every ton of dry cocoa beans obtained (Sánchez et al., 2023). Therefore 74% of produced biomass is dry residue (Campos-Vega et al., 2018). Global cocoa production has exhibited consistent growth over the years, growing from over 1.2 million tonnes in 1961 to 5.6 million tonnes in 2019 (Gaia Cacao, 2021). In 2022/23 it was estimated a production of 4.9 million tonnes of cocoa beans (ICCO, 2023). Based on these values, the quantity of dried cocoa residues generated in the 2022/23 season was 12.42 million tonnes, nearly 62 million tonnes of fresh material. Residue management does not just bring environmental concerns but also has economic implications, ranging from yield losses attributed to disease spread resulting from inadequate management practices to the requirement for residue treatment facilities equipped with trained personnel and new equipment (Acosta et al., 2018; Valadez-Carmona et al., 2018; Sánchez et al., 2023).

Figure 1. Different parts of coffee include coffee skin, pulp, beans covered with mucilage (a), and fresh beans (b). Kateshi Estate, Zambia (Photos by Nicolas Wittmann).

Concerning the environmental risks, post-harvest residues and waste can lead to pollution of water bodies when the wastewater is improperly disposed of, as the organic matter can seep into water bodies, impacting aquatic ecosystems (Genanaw et al., 2021). Besides, the leaching of nutrients into the soil under the compost heap may also occur, especially K, preventing their cycling back to the plantation (Hougni et al., 2021). Hougni et al. (2021) showed that 11% of K was leached within 48 hours from fresh husks and 92% from partially decayed husks. Additionally, if left to decompose in anaerobic conditions, the residues release CH_4 and N_2O, both potent GHGs (San Martin Ruiz et al., 2020; 2021). The global warming potential of CH_4 is 27 times higher than CO_2 over a 100-year horizon (27 kg $CO_{2\text{-eq}}$ kg^{-1} CH_4) (Figure 3) (Forster et al., 2021). N_2O is both an ozone-depleting substance

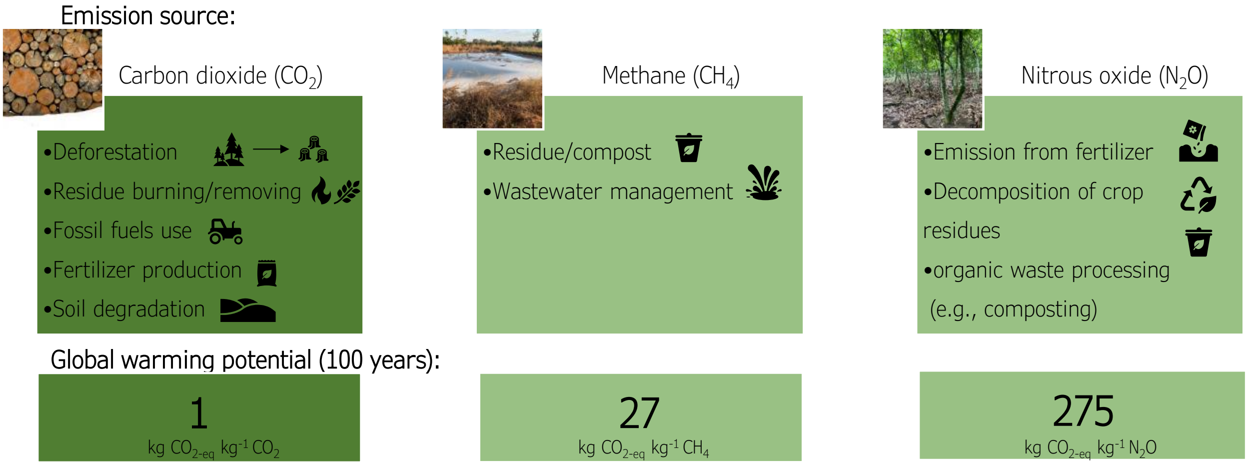
(Ravishankara et al., 2009) and a GHG with a global warming potential 273 times greater than that of CO_2 (Forster et al., 2021). Accompanying emissions of non-GHG air pollutants, such as ammonia (NH_3) and volatile organic compounds (VOCs), are also important due to their impact on air quality and their role in human health (Nordahl et al., 2020).

At the same time, the coffee and cocoa residues also offer opportunities for sustainable innovations through recycling alternative products, contributing to a circular economy (Iriondo-DeHond et al., 2020; Sengupta et al., 2020). They can be repurposed into valuable resources when processed properly. For example, coffee pulp and cocoa pods can be composted and redistributed as a soil conditioner and nutrient source to enhance soil fertility, water retention and structure (Pulleman et al., 2023). As such, compost can replace part of the mineral fertilizers required for coffee and cocoa production. The residues can also be used to feed black soldier fly larvae (*Hermetia illucens*), bioconverting organic residues into protein-rich biomass and insect frass to be used as animal feed and compost, respectively. Anaerobic digestion can convert the residues into biogas, serving as a renewable energy source. The digested material can be returned to the farm as an organic fertilizer (Pin et al., 2020; Pulleman et al., 2023), reducing reliance on non-renewable energy sources (Rattan et al., 2015; Ijanu et al., 2019). Another possibility is the production of biochar, which can in turn serve as a soil conditioner (Munongo et al., 2017; Campos et al., 2021; Pinzon-Nuñez et al., 2022).

This report provides an overview of the residues generated during the processing of coffee and cocoa, from harvest to green/dried beans, detailing common residue management practices employed by farmers. We delve into their environmental impact related to GHG production, specifically focusing on CH_4 and N_2O emissions. Post-harvest processing can occur *on-farm* or *off-farm* in centralized processing plants. This has important implications for the feasibility of different technologies to reduce GHG emissions. The main objective of this report is to identify the main points of environmental concern and to suggest methods for monitoring GHG emissions from residues. Understanding the GHG emissions throughout the entire life cycle of coffee and cocoa industry products, including residue management practices, is crucial for developing sustainable solutions and reducing environmental impact.

Figure 2. Different parts of cocoa fruit, cocoa closed pods (a), cocoa beans covered with mucilage (b), cocoa pod husk (c), and cocoa beans and Cocoa bean shell (d). Tiassalé, Côte d'Ivoire (Photos by Kakira Ouattara).

Figure 3. Greenhouse gases emitted from agriculture activities, their most important sources relevant to coffee and cocoa farming, and their global warming potential. Adapted from Pulleman et al. (2023).



2. Exploring coffee processing methods and residue/waste management

2.1. Coffee processing methods

Various coffee processing methods are employed globally, influenced by both the country of origin and the desired characteristics of the beans. The processing of coffee beans encompasses three principal techniques: dry, semi-wet (semi-washed or pulped natural), and wet methods (washed) (Rattan et al., 2015; Echeverria and Nuti, 2017; Ijanu et al., 2019; Campos et al., 2021). Among these, the washed method stands out for its capacity to yield coffee beans of exceptional quality. To illustrate, in Brazil, the predominant approach revolves around the dry method, primarily aimed at maximizing production output. In contrast, coffee-producing nations such as Colombia and Costa Rica prioritize the attainment of high-quality coffee beans. This objective drives the utilization of both the "washed method" and the "semi-washed method" during processing.

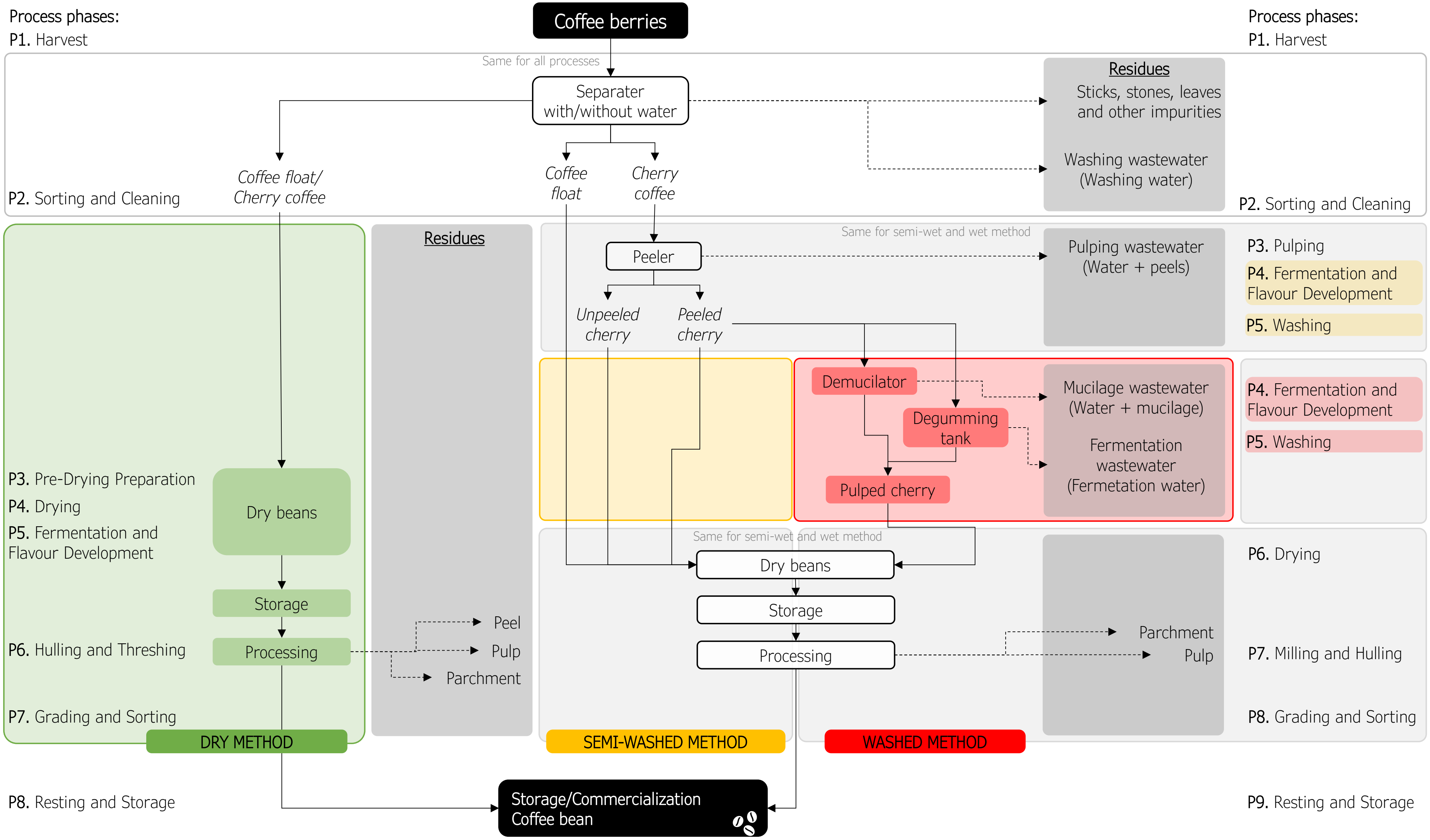
Dry method of coffee processing

The dry method of coffee processing, also known as the “natural processing method”, is a traditional approach used to treat coffee beans mainly in Brazil, Ethiopia, and Haiti (Figure 4) (Campos et al., 2021). It involves sun-drying freshly harvested coffee cherries with their outer layers intact, facilitating the removal of the dried husk after the drying phase. The main processing steps are:

Main dry method steps:

- *P1. Harvest:* The process begins with the selective harvesting of ripe coffee cherries from coffee plants (Figure 4, P1);
- *P2. Sorting and Cleaning:* Once harvested, the cherries undergo sorting to remove any damaged, underripe, or overripe cherries (Figure 4, P2). This step ensures that only high-quality cherries proceed to the next stage. In this process water can be used to clean the coffee cherries, generating two types of residues: sticks, stones, leaves and other impurities and washing wastewater (Campos et al., 2021);
- *P3. Pre-Drying Preparation:* The sorted cherries are evenly spread out in thin layers on drying surfaces (Figure 4, P3). These surfaces can vary from traditional patios to raised drying beds. The goal is to facilitate efficient drying by exposing the cherries to sunlight and airflow;
- *P4. Drying:* The exposed cherries are left to dry naturally under the sun (Figure 4, P4);
- *P5. Fermentation and Flavour Development:* During the drying phase, the cherries undergo significant changes, including enzymatic reactions within the fruit's pulp. As the cherries dry, enzymes in the fruit's mucilage become active (Figure 4, P5). The enzymic reactions lead to the fermentation of sugars and other compounds. This fermentation process is pivotal in creating the distinctive flavours and aromas associated with dry-processed coffees. Once the cherries reach the desired moisture content —usually around 11% — they are sufficiently dry, typically after 3–4 weeks, depending on the drying conditions (Alves et al., 2017). It is worth noting that many Brazilian producers dry the coffee beans (*Coffea canephora* /Robusta coffee) within 24 hours through forced drying in wood-fired ovens that push hot air into huge drum dryers;
- *P6. Hulling and Threshing:* This step involves removing the dried pulp from the beans (Figure 4, P6). This can be achieved through mechanical processes or manual threshing, revealing the green coffee beans. In this process three different types of residues are generated, coffee peel, pulp and parchment;
- *P7. Grading and Sorting:* The extracted beans are sorted based on size, quality, and any visible defects (Figure 4, P7);
- *P8. Resting and Storage:* The processed coffee beans are then allowed to rest for a period to stabilize their moisture content and flavour characteristics (Figure 4, P8).

Figure 4. Flow diagram showing coffee processing steps and the residues produced during various steps using the "dry method", "semi-washed method" or "washed method". The key steps that produce most of the effluent and solid residue have been indicated. Coffee float consisting of dry coffee, super-ripe, and almost dry fruits, called "raisin", badly-grated fruits, and green and ripe fruits with only one developed seed. Source: Adapted from Campos et al. (2021), Echeverria and Nuti (2017), and Rattan et al. (2015).



Semi-washed method of coffee processing

The semi-washed method of coffee processing, also known as the "pulped natural" method, is a hybrid approach that combines elements of both the dry and washed methods (Figure 4) (Campos et al., 2021). This method aims to strike a balance between preserving some of the fruity characteristics of the coffee cherry while reducing the risk of defects often associated with the dry method. As in other processing methods, the process starts with:

Main semi-washed method steps:

P1. *Harvest:* Collecting ripe coffee cherries from coffee trees (Figure 4, P1);

P2. Sorting and Cleaning: The cherries are sorted to remove any damaged or underripe ones, ensuring only high-quality cherries are processed (Figure 4, P2);

P3. *Pulping:* Unlike the dry method, the semi-washed method involves removing the outer skin of the cherry soon after harvesting (Figure 4, P3). This is achieved through mechanical pulping machines. The result is a mix of mucilage-covered beans and the inner parchment layer;

P4. *Fermentation and Flavour Development:* After pulping, the beans, still covered in mucilage, are subjected to a fermentation period (Figure 4, P4). This fermentation allows some of the mucilage to be broken down and absorbed by the beans, contributing to their flavor profile;

P5. *Washing:* Following fermentation, the beans are washed to remove any residual mucilage (Figure 4, P5). This washing step helps to reduce the chances of over-fermentation and defects. The washed beans are then separated based on density, with higher-quality beans sinking to the bottom;

P6. *Drying:* The washed beans are spread out to dry, similar to the dry method (Figure 4, P6). However, the beans still have a thin layer of parchment surrounding them;

P7. *Milling and Hulling*: Once the beans reach the desired moisture content, the parchment layer becomes brittle. The beans are then mechanically hulled to remove the parchment and reveal the green coffee beans (Figure 4, P7);

P8. *Grading and Sorting:* The green beans are sorted based on size, density, and quality (Figure 4, P8);

P9. *Resting and Storage:* Similar to other processing methods, the graded beans are allowed to rest before being stored (Figure 4, P9).

The semi-washed method allows for some of the fruit's characteristics to be imparted to the beans while reducing the risk of defects that can occur in the dry method. The main residues generated during the semi-washed method are sticks, stones, leaves, and other impurities and washing wastewater during the "*Sorting and Cleaning Phase*", Peeling wastewater (Water + peels) generated during the "*Pulping Phase*" and the last residues are the pulp and parchment during "*Hulling and Threshing Phase*" (Figure 4).

Washed method of coffee processing

The washed method of coffee processing is a meticulous and labour-intensive process used to extract coffee beans from the coffee cherry's fruit pulp. This method is known for producing coffees with cleaner flavours, brighter acidity, and increased consistency compared with other processing methods. The washed method involves several distinct stages (Figure 4) (Campos et al., 2021).

Main washed method steps:

P1. *Harvest:* The process begins with the selective harvesting of ripe coffee cherries from coffee plants (Figure 4, P1);

P2. *Sorting and Cleaning:* After harvesting, the cherries are cleaned and sorted (Figure 4, P2);

P3. *Pulping:* cherries are pulped to remove the outer fruit layer (Figure 4, P3). This can be done using machines or traditional methods such as hand-cranked pulpers. The result of this process is a mixture of beans covered in sticky mucilage;

P4. *Fermentation and Flavour Development:* The pulped beans, still covered in mucilage, are then transferred to fermentation tanks (Figure 4, P4). This fermentation stage allows enzymes to break down the remaining mucilage, which enhances the beans' flavours and removes any unwanted flavours;

P5. *Washing:* After fermentation, the beans are thoroughly washed to remove any leftover mucilage (Figure 4, P5). This washing is typically done with clean water, either through immersion or running water channels;

P6. *Drying:* The washed beans are spread out on drying beds or patios to reduce their moisture content (Figure 4, P6);

P7. *Milling and Hulling*: Once the beans are dried to the desired moisture level, they are milled to remove the protective parchment layer that surrounds each bean (Figure 4, P7). This exposes the green coffee beans;

P8. *Grading and Sorting:* The beans are sorted and graded based on their size and quality. The coffee beans are sorted to remove any defects or off-grade beans (Figure 4, P8);

P9. *Resting and Storage:* the graded and sorted beans are allowed to rest before being stored (Figure 4, P9).

The washed method of coffee processing is favoured in regions where water is abundant. While the washed method produces high-quality coffee, it also requires more resources, time, and labour compared to other processing methods. However, the potential for exceptional flavours and the ability to create consistent coffee profiles make the washed method a popular choice among speciality coffee producers. While the washed method yields good quality ‘clean cup’ coffee, it also generates specific residues and byproducts that need proper management to minimize environmental impact (Figure 4).

It is noteworthy that various coffee processing methods have been developed to mitigate environmental impacts, including the development of eco-demucilagers and eco-washers. The first employ mechanical means to remove mucilage, significantly reducing water consumption as berries undergo minimal submerged fermentation. Meanwhile, the eco-washer technology optimizes water usage during pulping and post-wet fermentation washing. While this method does involve water usage in wet fermentation, it still requires less water compared to conventional washing (Pulleman et al., 2023). The washed method is primarily employed in Arabica (*Coffea arabica*) processing, while it is less common in Robusta (*Coffea canephora*) processing, although its use in Robusta is gradually increasing. High-quality Robusta coffee remains as a niche market, but there is a growing interest in its production. Robusta coffee, characterized by higher mucilage content, poses greater challenges in the removal process.

2.2. On-farm management of coffee residues/byproducts

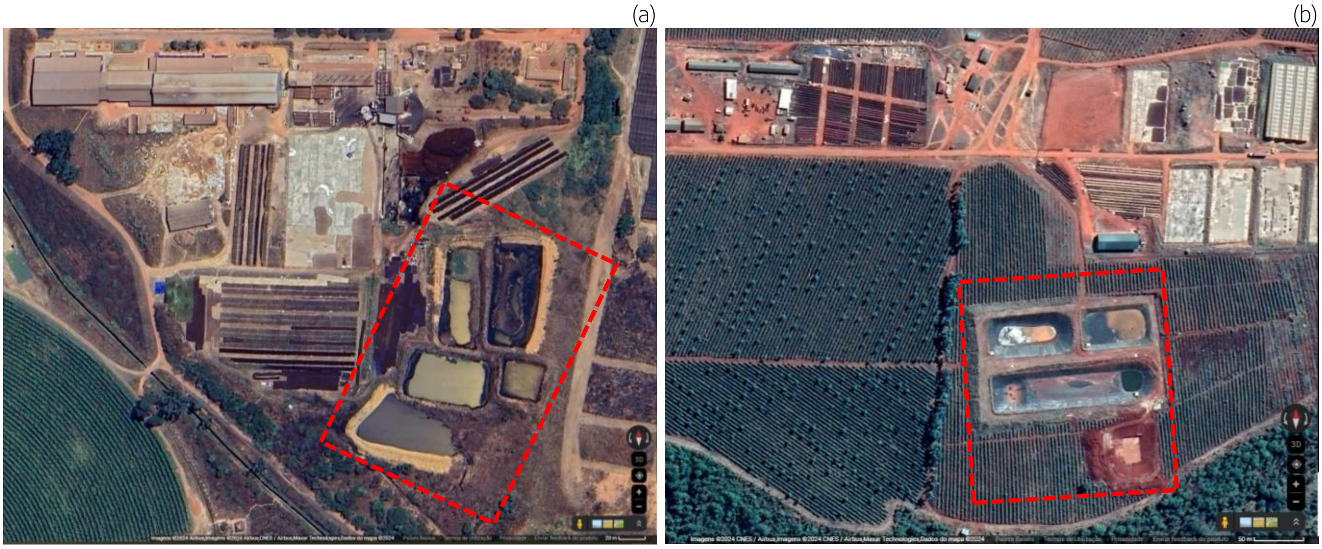
Irrespective of the chosen processing route, the coffee production process inevitably generates residual byproducts (Rattan et al., 2015; Echeverria and Nuti, 2017; Ijanu et al., 2019) (Figure 4). Notably, the husk (Figure 5) and wastewater (Figures 6, 7) represent the principal residue products generated during these processes. The specific approach to managing these residue products can vary based on the specific agricultural practices of each farm (Iriondo-DeHond et al., 2020; Serna-Jiménez et al., 2022).

At the initial stages of coffee processing, regardless of the method used (dry, semi-washed, or washed), residues such as "sticks, stones, leaves, and other impurities" are generated. These solid residues are typically collected and piled up, as illustrated in Figure 5. While Figure 5 portrays the scenario on large coffee farms, the situation may vary considerably on smallholder farms, although the underlying principles remain similar. Besides, there is also the production of "washing wastewater". When water is involved in the process, the liquid residue is directed to decantation tanks, as shown in Figures 6 and 7. The resulting wastewater primarily consists of water used to clean coffee cherries, along with impurities like dust and soil. Since this residue primarily contains water with low organic matter content, it usually does not pose significant environmental concerns on its own.

Figure 5. Solid residue from coffee production. Coffee parchment (light brown) (a, b, d) and coffee pulp (dark brown) (c). (Farm in Kateshi Estate, Zambia, photos by Nicolas Wittmann).

Figure 6. Wastewater ponds in Zambia (Picture from Kateshi farm in Zambia, photos by Piet van Asten).

Figure 7. Interconnected wastewater ponds from space in Zambia (NCCL farm, 10°01'06.4"S 31°12'37.5"E, https://maps.app.goo.gl/tjFy6ttXbPW6GuoY6) (a) and Tanzania (Aviv farm, 10°43'00.5"S 35°15'42.6"E, https://maps.app.goo.gl/LG8fb33PhPhXUY6t9) (b).



The next residue is the “peeling wastewater” or "depulping wastewater". By definition, peeling wastewater is the water used in the process to remove the outer fruit layer. This residue is produced during semi-washed and washed methods. The wastewater is generated during the process of removing the outer skin or peel of coffee cherries to extract the beans inside (process of depulping), and it is one of the initial steps in coffee processing. During depulping, water is used to transport the cherries through the depulping machine and separate the beans from the outer skin. This process generates wastewater that contains residues from the coffee cherries, including bits of the skin/peel, pulp, and mucilage. Peeling wastewater needs to be treated before it is released into the environment due to its high organic matter content. The most common treatment involves sedimentation tanks and filtration systems to remove solids and contaminants from the wastewater (Figure 8).

After depulping, the mucilage which is a sticky, sugary substance surrounding the coffee beans is removed through fermentation. Beans are typically placed in fermentation tanks filled with water and naturally occurring enzymes break down the mucilage, causing it to detach from the beans and dissolve it into the water. The liquid that results from the fermentation process, which contains the dissolved mucilage, is referred to as “mucilage/fermentation wastewater”. This wastewater is typically sticky and viscous due to the presence of mucilage and other organic matter. The methods used to treat these residues are similar to the treatments used to treat peeling wastewater. The mucilage itself consists of sugars, pectins, and other organic compounds from the cherry's fruit pulp. In some coffee-producing regions, this mucilage is not considered residue but is used for various purposes. For example, it can be recycled as a nutrient-rich component in composting or used as animal feed.

During the dry process method, the last residues produced are the "peel, pulp and parchment residue" (husk residue). These residues consist of the outer layers of the coffee cherry, which are no longer needed once the beans have been separated. In the semi-washed and washed coffee processing methods, the first step involves removing the outer skin (peel) from the cherries using depulping machines along with water. “pulp and parchment residue” is generated at the end of the coffee processing. The treatment or disposal of solid residue from the dry, semi-washed, and washed coffee processing methods is generally similar. Typically, farmers leave these residues in piles near the processing facilities, where they may potentially function as a natural composting system, albeit without proper management. In Brazil, in the case of a nearby chicken farm, some coffee farmers donate the husk to be used as chicken bedding, and then the poultry litter is returned to the coffee plantation as organic fertilizer. Some coffee producers may explore options such as composting, using the residue for mulch, or even converting it into bioenergy either directly or by making pellets to sell as fuel.

The most common method for treating wastewater residues is through the use of sedimentation tanks designed to remove solids and contaminants from the wastewater (see Figure 8, 9). The primary objective of this process is to reduce the organic matter content. The standard recommendation is to have four successive ponds to effectively decrease the organic matter content. The coffee wastewater residues have Chemical Oxygen Demand (COD) of up to 22,000 mg L^{-1} and biological oxygen demand (BOD) of up to 12,500 mg L^{-1} (Tekle et al., 2015; Sengupta et al., 2020; Genanaw et al., 2021). The liquid residues generated during the coffee processing season are initially released into the first pond (Figure 9, Pond 1). Subsequently, the excess water flows into other ponds to reduce the risk of organic-

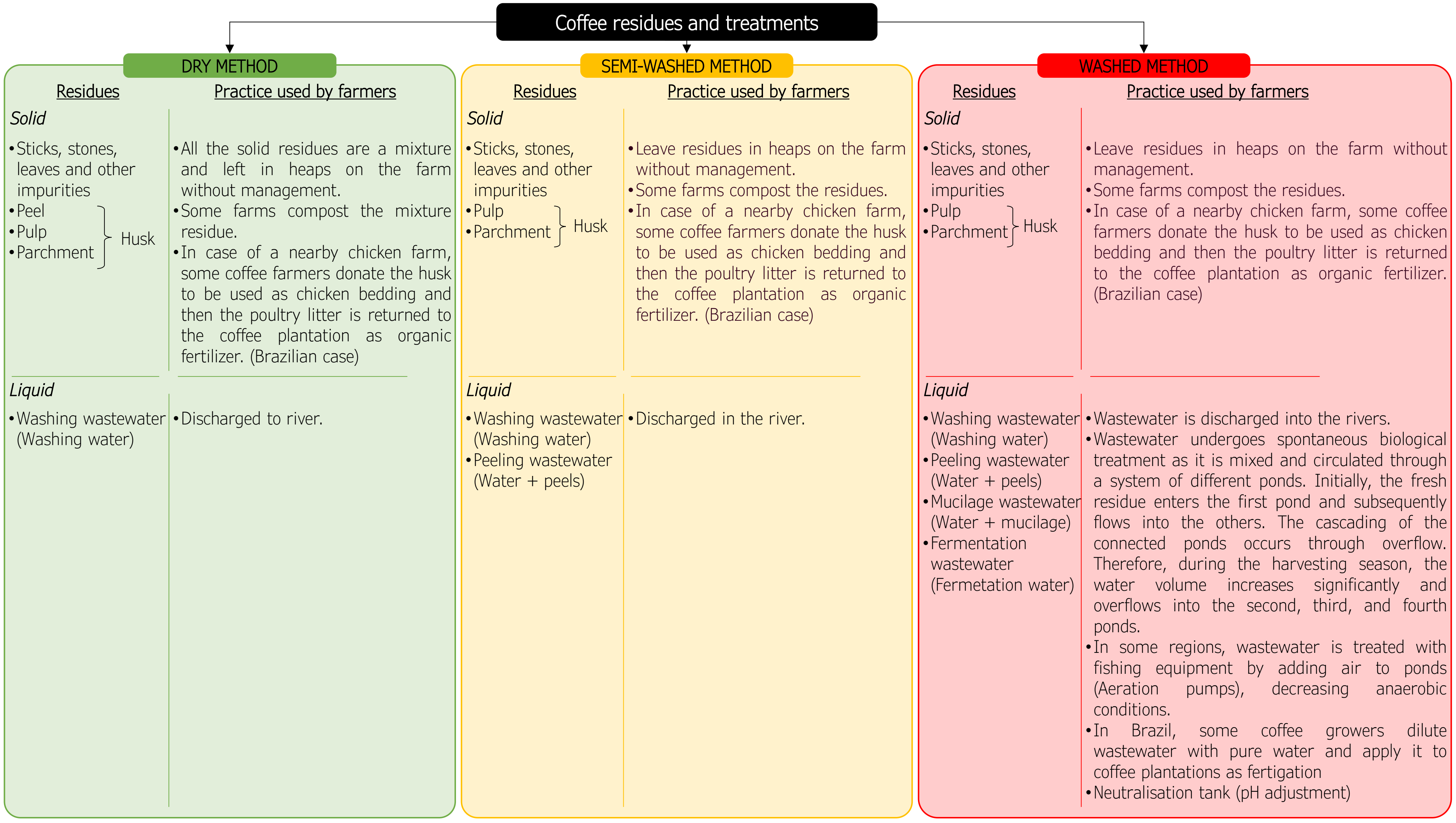


Figure 8. Residues of coffee production and common practices used by coffee producers around the world. The main destination of each residue generated in each coffee processing step is described. The methods described here represent current situations around the world

Coffee residues and treatments

DRY METHOD

	Residues	Practice used by farmers
Solid	Sticks, stones, leaves and other impurities Peel, Pulp, Parchment } Husk	All the solid residues are a mixture and left in heaps on the farm without management. Some farms compost the mixture residue. In case of a nearby chicken farm, some coffee farmers donate the husk to be used as chicken bedding and then the poultry litter is returned to the coffee plantation as organic fertilizer. (Brazilian case)
Liquid	Washing wastewater (Washing water)	Discharged to river.

SEMI-WASHED METHOD

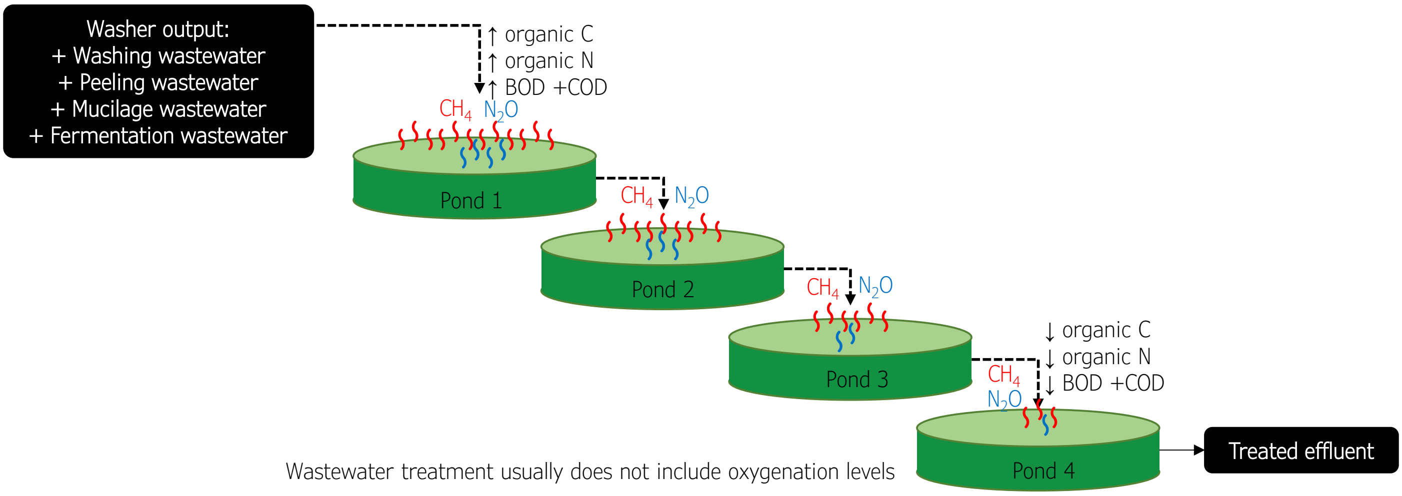
	Residues	Practice used by farmers
Solid	Sticks, stones, leaves and other impurities Pulp, Parchment } Husk	Leave residues in heaps on the farm without management. Some farms compost the residues. In case of a nearby chicken farm, some coffee farmers donate the husk to be used as chicken bedding and then the poultry litter is returned to the coffee plantation as organic fertilizer. (Brazilian case)
Liquid	Washing wastewater (Washing water) Peeling wastewater (Water + peels)	Discharged in the river.

WASHED METHOD

	Residues	Practice used by farmers
Solid	Sticks, stones, leaves and other impurities Pulp, Parchment } Husk	Leave residues in heaps on the farm without management. Some farms compost the residues. In case of a nearby chicken farm, some coffee farmers donate the husk to be used as chicken bedding and then the poultry litter is returned to the coffee plantation as organic fertilizer. (Brazilian case)
Liquid	Washing wastewater (Washing water) Peeling wastewater (Water + peels) Mucilage wastewater (Water + mucilage) Fermentation wastewater (Fermetation water)	Wastewater is discharged into the rivers. Wastewater undergoes spontaneous biological treatment as it is mixed and circulated through a system of different ponds. Initially, the fresh residue enters the first pond and subsequently flows into the others. The cascading of the connected ponds occurs through overflow. Therefore, during the harvesting season, the water volume increases significantly and overflows into the second, third, and fourth ponds. In some regions, wastewater is treated with fishing equipment by adding air to ponds (Aeration pumps), decreasing anaerobic conditions. In Brazil, some coffee growers dilute wastewater with pure water and apply it to coffee plantations as fertigation Neutralisation tank (pH adjustment)

rich water overflowing into streams or rivers. However, in many cases, farmers have only a single pond on their farms. At the end of the season, after many months of spontaneous decomposition of organic matter, the liquid residue is usually released into nearby rivers (Alemayehu et al., 2020). The process occurs once the water is 'safe' – i.e. the BOD has decreased. One possibility is to use this liquid residue as organic fertilizer through fertigation. However, coffee trees are sensitive, and it is uncommon to use the wastewater residue in the plantation in its current state. Fresh wastewater typically has high COD and is often acidic. This can create anaerobic and acidity problems for rooting systems if irrigated abundantly. Some preliminary results have shown that diluting wastewater or using limited quantities has no negative impact on plant growth and helps recycle nutrients. Further research is essential to explore the feasibility of utilizing treated wastewater for irrigation. Moreover, water conservation measures represent a key strategy for minimizing environmental impacts by reducing wastewater generation from the outset.

Figure 9. Most common method of treating coffee wastewater. Washer output after the washing and fermentation of the beans, three water treatment ponds (Pond 1, Pond 2 and Pond 3) and the effluent after spontaneous biological treatment (Pond 4).



2.3. Alternative methods for handling coffee residues/byproducts

Despite the common treatments chosen by farmers, different ones can be used to treat the solid and liquid residues from coffee production (Table 1). Some residues remain underutilized, possibly due to a lack of recognition of their potential or the dominance of other residues. Each treatment has a different cost, feasibility, efficiency and environmental problems (Rattan et al., 2015; Echeverria and Nuti, 2017; Ijanu et al., 2019; Pires et al., 2019; Iriondo-DeHond et al., 2020; Pin et al., 2020; Sengupta et al., 2020; Campos et al., 2021; Serna-Jiménez et al., 2022; Said et al., 2023). Both physical and chemical treatments are usually unable to completely remove contaminants; therefore, their combined use is required in some cases (Said et al., 2023). For further information, there are additional treatments described by Pulleman et al. (2023), Said et al. (2023), Serna-Jiménez et al. (2022), Campos et al. (2021), Sengupta et al. (2020) and Echeverria and Nuti (2017) and Rattan et al. (2015). Below, the main possible treatments to be used are described and alternative options are mentioned:

SOLID RESIDUES:

Mulching	•Utilizing coffee residues as mulch in coffee plantations is a beneficial practice that aids in soil moisture conservation, weed growth suppression, and improvement of overall soil quality (Esteca et al., 2018). Nevertheless, the use of fresh material can result in temporary N immobilization, and it involves transporting a larger volume back to the field, which may be a burden.
Composting	•Many coffee farmers recognize the value of coffee residues as an organic resource (San Martin Ruiz et al., 2018; 2021). They utilize composting techniques to convert these organic materials into nutrient-rich compost as mentioned before. This compost can then be returned to the coffee fields, improving soil health and fertility while reducing the need for chemical fertilizers (Jiang et al., 2023).
Vermicomposting	•Coffee farms can also use earthworms to break down the coffee residues into nutrient-rich vermicompost (Raphael et al., 2012; Hanc et al., 2021). This process can be faster than other methods of composting and yields a high-quality organic fertilizer. Using worms accelerates the decomposition process.
Bioenergy production	•In some regions, dried coffee parchment and husks are used as bioenergy sources (Chala et al., 2018; Mendoza Martinez et al., 2021; Serna-Jiménez et al., 2022). These residues can be burned to generate heat or converted into biofuels, providing an eco-friendly energy alternative and reducing the environmental impact of coffee waste.
Anaerobic digestion	•Coffee pulp can be used in anaerobic digesters to produce biogas and nutrient-rich residue (digestate) (Chala et al., 2018; Serna-Jiménez et al., 2022). This approach helps generate renewable energy while also creating a useful fertilizer.
Biochar	•Coffee husks can be used to produce biochar (Asfaw et al., 2019). Utilizing biochar for treating residues from coffee production not only presents an alternative disposal option but also holds the potential to enhance soil quality and contribute to C sequestration.
BSF larvae feed	•The residues can be used to feed black soldier fly (BSF) larvae (*Hermetia illucens*), bioconverting organic residues into protein-rich biomass and compost (Boakye-Yiadom et al., 2022). The biomass can serve as animal feed, while the compost can serve as fertilizer.

Table 1. List of treatments for processing coffee solid residue and wastewater.

Coffee by-product	*Residue treatment*
Solid	All solid residue is mixed and composted. (San Martin Ruiz et al., 2018; 2021)
Husk (peel, pulp and parchment residue)	In the case of a nearby chicken farm, some coffee farmers can donate the husk to be used as chicken bedding and then the poultry litter can return to the coffee plantation as organic fertilizer.
	Vermicomposting (Raphael et al., 2012; Hanc et al., 2021)
	Mulching (Esteca et al., 2018)
	Bioenergy production (Chala et al., 2018; Mendoza Martinez et al., 2021; Serna-Jiménez et al., 2022)
	Anaerobic digestion (Chala et al., 2018; Serna-Jiménez et al., 2022)
	Juice with the pulp
	Mushroom cultivation using coffee pulp/husks
	Biochar (Asfaw et al., 2019)
	BSF larvae feed (Boakye-Yiadom et al., 2022)
Liquid	
Washing water + water with peels, mucilage, and fermentation water	Wastewater ponds
	Filtration and sedimentation
	Adsorption using activated carbon
	Acidification pond (pH adjustment)
	Neutralisation tank (pH Adjustment)
	Chemical coagulation-flocculation
	Electrocoagulation
	Advanced oxidation process
	Anaerobic digestion
	Aerobic digestion
	Constructed wetland/ phytoremediation (Berego et al., 2022)
	Biogas and methane production from coffee wastewater (Park and Craggs, 2007; del Real Olvera and Lopez-Lopez, 2012; Novita, 2016)
	Fertigation

WASTEWATER RESIDUES:

Ponds

- Wastewater treatment using ponds involves several sequential steps. Initially, wastewater is allowed to stand, letting larger particles and sediments settle. Screens may remove these particles. Microorganisms then break down the organic matter (OM). However, other methods can also be used for this process.
- Common methods encompass: 1) Aerated Lagoons, these are large shallow ponds where aeration fosters the growth of beneficial microorganisms responsible for breaking down the OM; 2) Activated Sludge Process, utilizing aeration and mixing; and 3) Biofilters, wastewater is directed through media where microorganisms thrive and consume the OM. The subsequent step aims to eliminate any remaining contaminants, utilizing diverse techniques such as: 1) Filtration, sand or membrane filters are employed to remove finer suspended particles; 2) Chemical Treatment, coagulants and flocculants aid in settling remaining solids, while pH adjustment can enhance the precipitation of specific contaminants; and Advanced Oxidation Processes (AOPs), these involve the use of UV light, ozone, or other chemical treatments to break down complex organic compounds. The final phase before discharge is disinfection. Disinfection methods include chlorination, UV, and ozone treatment. Please bear in mind that specific treatment methodologies may vary depending on factors such as the wastewater composition, local regulations, and available resources (Echeverria and Nuti, 2017). Another possibility is use plants as biofilters, after the reduction of OM, the wastewater can go to wetlands (Berego et al., 2022).

Biogas and methane production from coffee wastewater

- The coffee wastewater can act as a source to generate biogas, a mixture of CH_4 and CO_2 and trace of H_2 (del Real Olvera and Lopez-Lopez, 2012; Novita, 2016; Echeverria and Nuti, 2017). There have been few studies showing the possibilities of CH_4 production from coffee wastewater. In oil palm plantations for example, some facilities install large "tents" over settling ponds to capture the CH_4 emissions and utilize it as biogas.

Fertigation

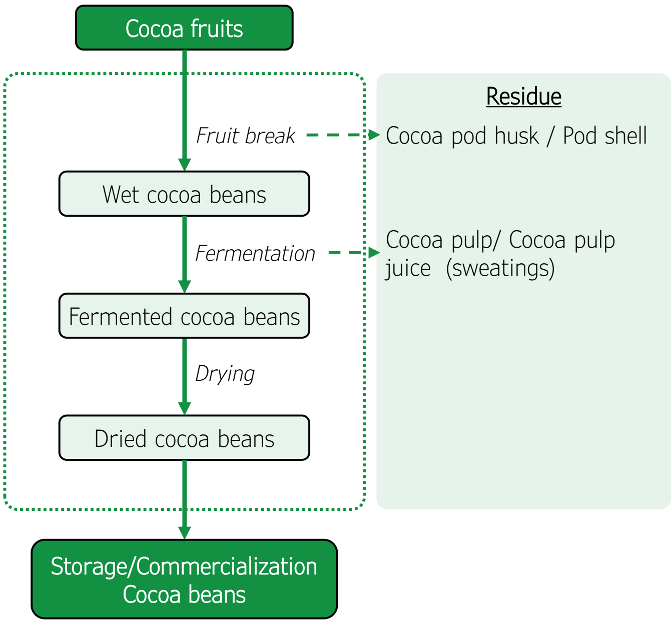
- The wastewater contains OM and essential nutrients like N and phosphorus (P), properly treated, it can act as a natural fertilizer, returning these nutrients to the soil. Fertigation also conserves freshwater resources, especially valuable in water-scarce regions. Correctly treated coffee wastewater can improve soil quality, potentially benefiting plant growth and soil health. However, if left untreated or managed poorly, conditions in soils which may harm the plant. Its nutrient composition also varies widely, posing difficulties in maintaining consistent nutrient levels, potentially leading to soil imbalances. It also important to coniderer the technology, as in drip irrigation, drippers could become clogged. The fertigation can be an option after all the treatments mentioned above.

3. Exploring on-farm cocoa processing methods and residue management

3.1. Cocoa processing methods

Cocoa processing on farms is less complex compared with coffee, requiring fewer steps (Figures 10 and 11) (Beg et al., 2017). However, these steps are crucial because they significantly impact the flavour quality attributes of cocoa beans and, consequently, the chocolate and other products. The post-harvest processing on farms normally includes three steps: (i) pod splitting and bean removal, (ii) bean fermentation, and (iii) drying. After these steps, the dried beans are transported to the industries and undergo a series of equipment to transform into a final product (Oddoye et al., 2013; Beg et al., 2017; Vásquez et al., 2019; Mariatti et al., 2021; Porto de Souza Vandenberghe et al., 2022). It is worth mentioning that there are also farmers who sell the cacao "en baba," and thus only step 1 is carried out on the farm.

Figure 10. Flow diagram showing cocoa processing steps and the residues produced during various steps. The key steps that produce most of the residue have been indicated. Source: Adapted from Sánchez et al. (2023) and Beg et al. (2017).



Cocoa harvesting is typically performed manually using machetes or similar tools. It involves the careful collection of ripe cocoa pods from the trees (Beg et al., 2017). The next step involves opening the ripe pods to extract the cocoa beans. This can be done manually using a machete or any other suitable tool to crack open the pods (Figure 10). The beans are surrounded by a white sweet-tasting pulp (Figure 2). The fresh beans, along with the pulp, are then placed in shallow wooden boxes and left to ferment for several days, or placed in heaps or bags, often covered with leaves of plantain or bananas (Figure 12). The box method usually is employed in Asia and Latin America, whereas the heap method is preferred in Africa (Oddoye et al., 2013; Beg et al., 2017; Vásquez et al., 2019; Mariatti et al., 2021; Porto de Souza Vandenberghe et al., 2022). However, the box method is becoming more common in Africa. Fermentation is a crucial step for developing the flavour quality attributes of commercial cocoa beans (development of aroma, colour, and flavours) and for removing the mucilaginous pulp (liquefaction). This process typically spans 3–7 days. After fermentation, the next step in the cocoa processing chain is drying. Once fermented, the beans are laid out in the sun for drying or through the hot air oven drier to prevent deterioration from bacteria, which typically marks the final step at the farm. This crucial step is necessary to reduce the moisture content of the beans, allowing them to be stored and processed further. Subsequently, the dried beans are packed into sacks for storage in warehouses and eventually exported to various countries. Depending on the cocoa variety, a single pod can contain anywhere from 20 to 50 beans. To produce 1 kg of dry beans, approximately 20 pods are required.

Figure 11. Pictures of the flow diagram showing cocoa processing steps and the residues produced during various steps. (Photos by Késia S. Lourenço and Matti Barthel).

Figure 12. Fermentation methods, shallow wooden boxes (a) and heaps (b). (Photos by Mirjam Pulleman and Matti Barthel).

3.2. On-farm management of cocoa residues

The residual biomass resulting from cocoa production and processing predominantly comprises cocoa pod husk, cocoa mucilage (often called pulp), and cocoa bean shells. Specifically, on the farm, the generated residues are cocoa pod husk and cocoa mucilage. During the fermentation of the mucilage, a cloudy liquid known as "sweating" is also produced. (Figure 11). Cocoa pod husk is the remaining material from the mature fruit after the extraction of cocoa beans and pulp, constituting approximately 70 to 80% of the entire fruit (Oddoye et al., 2013; Sánchez et al., 2023). It consists of four layers: epicarp, mesocarp, sclerotic, and endocarp, and it serves as a significant reservoir of bioactive compounds and fibrous material. The mucilage is abundant in sugars and minerals, making it highly suitable for fostering the growth of microorganisms and for making juice or icecream (Martínez et al., 2012; Oddoye et al., 2013; Vásquez et al., 2019).

The destination of the residues depends on the farmers' practice at harvest. Farmers can harvest the pods, open them directly, extract the beans near the trees, and leave the pods behind in the field, abandoning them on the plantations at the place of cocoa stripping, which is a common practice in Ecuador. Alternatively, they may harvest the pods and transport them to a central place, usually located in the same field, where they are accumulated in large piles. This is the most common process in Africa (Figure 12). The large piles of husks remaining after breaking the fruits are typically left to decompose on the farms without proper management. However, they can be composted and returned to the fields to enhance soil structure and incorporate organic matter, increasing soil health. After the fermentation stage, the mucilage is also left behind on the farm and subsequently discarded in the environment.

Figure 13. A pile of cocoa pod husks (a) and location for fermenting the cocoa beans and collecting the cocoa pulp juice, a cloudy liquid known as 'sweating' (b), on a farm in Côte d'Ivoire (August 2023) (Photos by Késia S. Lourenço).

3.3. Alternative methods for handling cocoa residues

Similar to coffee, despite the residue management practices currently chosen by farmers, various methods can be employed to treat the solid residues generated from cocoa. In the cocoa industry, certain residues, although rich in potential, often remain underutilized. To achieve complete sustainability, all residues should be utilized and recycled. Below we briefly mention some of the possible methods:

Composting

- The cocoa residues can be composted on the farm to produce a rich organic residue that can be used by the farmer. This compost can then be returned to the cocoa fields, improving soil health and fertility while reducing the need for chemical fertilizers (Fidelis and Rajashekhar Rao, 2017; Doungous et al., 2018). However, it is crucial to ensure that pathogens are killed, which is one reason why farmers may be reluctant to engage in this practice.

Vermicomposting/ Millicomposting

- Cocoa farms can also utilize vermicomposting or millicomposting, where earthworms or other animals, such as millipedes, beetles, and certain insect larvae, break down the residues into nutrient-rich vermicompost (Ashwini and Sridhar, 2006; Raphael et al., 2012; Hanc et al., 2021). This process can be faster than traditional composting and yields a high-quality organic fertilizer. Using small animals to break down crop residues can accelerate the decomposition process.

Biochar

- Another beneficial use for cocoa pod husks is their conversion into biochar. Biochar is obtained through heating biomass under oxygen-deficient conditions. Biochar has enormous potential as a source of nutrients, a soil conditioner, a waste management solution, and an agent for long-term C sequestration. Studies have shown that biochar enhances soil structure and fertility when used as a soil amendment (Ayeni et al., 2008; Atkinson et al., 2010; Munongo et al., 2017; Pinzon-Nuñez et al., 2022). By converting cocoa pod husks into biochar, as well as compost, the husks are disinfected during production due to the high temperatures, reducing pathogen levels, especially *Phytophthora*, which causes black pod disease in cocoa. In cases where cocoa pod husks are contaminated with Cd, biochar can also assist in the remediation of heavy metals from agricultural soils (Pinzon-Nuñez et al., 2022).

Animal feed

- In certain cases, cocoa husks may be used as supplementary feed for livestock, contributing to their diet's fiber content (Oduro-Mensah et al., 2020). Cocoa husk can be a valuable substitute to a cereal-based diet with no effect on feed intake, weight gain, and feed efficiency (Oddoye et al., 2010; Magistrelli et al., 2016).

Others

- Numerous studies have identified cocoa bean husks as a promising source of bioactive compounds including theobromine, phenols, as well as cell wall components like lignin, cellulose, and hemicellulose. The components can be used in the food, cosmetic, and pharmaceutical sectors. There are further treatments available for managing the residues generated during cocoa production.

For more detailed information, please refer to Porto de Souza Vandenberghe et al. (2022), Mariatti et al. (2021), and Campos-Vega et al. (2018).

4. Environmental challenges of coffee and cocoa residue handling

As explained above, the management of coffee and cocoa residue by farmers is a crucial aspect of sustainable food production which has significant environmental concerns. Two essential factors must be considered: responsible residue handling and the issues caused by improper disposal in the environment. These issues are often overlooked when calculating the C footprint for coffee and cocoa production. Little is known about the emissions of GHGs during the residue and wastewater treatment on the farm, particularly of CH_4 and N_2O (Table 2). Regarding GHGs, we mainly focus on CH_4 and N_2O emissions because they are the primary drivers of net climate-forcing impacts resulting from composting and emissions after applying the compost to the soil (Boldrin et al., 2009; Preble et al., 2020). In contrast, C emitted as CO_2 during composting is not thought to have a net climate impact, because it is considered part of the natural C cycle. The C emitted as CO_2 during decomposition is initially taken from the atmosphere by plants during photosynthesis. As a result, the C released during composting is essentially returning to the atmosphere, creating a cycle rather than adding new CO_2 to the system.

Table 2. Expected relative magnitude of methane (CH_4) and nitrous oxide (N_2O) emissions from the coffee and cocoa residues under different management practices.

	Processing method	Residue type	Residue treatment	Expected CH_4 and N_2O emissions[a]				
				None	Low	Moderate	High	Very high
Coffee	Dry method: Coffee is dried and then milled	Coffee husk (skin/peel, pulp, and parchment)	Dry weather condition		CH_4 & N_2O			
		Coffee husk (skin/peel, pulp, and parchment)	Piles are left on the farm for a long period; during the rainy season, they can re-wet.				CH_4 & N_2O	
	Semi-washed method: Coffee is pulped when still fresh.	Pulp & parchment	Fresh pulp heaps that are very wet					CH_4 & N_2O
		Wastewater	The liquid residue goes to ponds		N_2O			CH_4
	Washed method: Coffee is pulped, fermented and washed	Pulp & parchment	Fresh pulp heaps that are very wet					CH_4 & N_2O
		Wastewater	The liquid residue goes to ponds		N_2O			CH_4
Cocoa		Fresh pod husk	Pods are left abandoned on the plantations after cocoa stripping		CH_4 & N_2O?			
			Pods are transported to a central station where they accumulate in large piles				CH_4 & N_2O	
		Mucilage	Left behind on the farm, discarded on the ground			CH_4 & N_2O?		
		sweating (cloudy liquid)	Left behind on the farm, discarded on the ground				CH_4 & N_2O?	

[a] The emissions of CH_4 & N_2O are expected to follow similar patterns, except in completely anaerobic conditions (ponds) where N_2 will be produced instead of N_2O.

[?] Little is known about N_2O in such conditions.

4.1. Solid residues

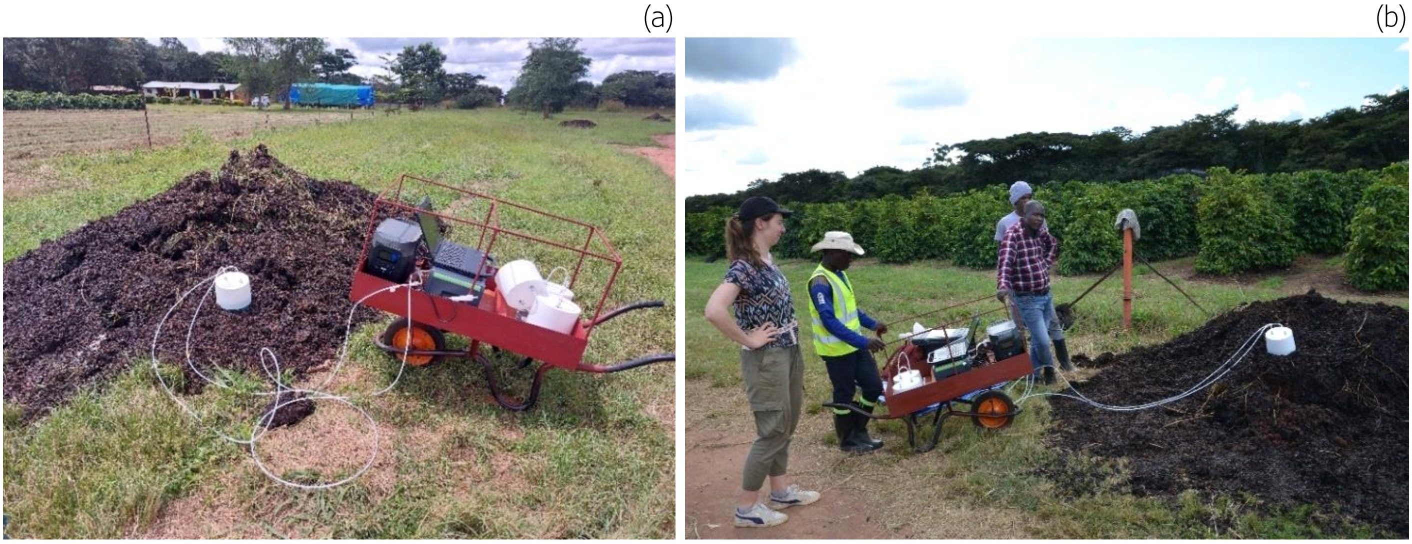
After harvest, coffee cherries and cocoa ponds are often aggregated and further processing takes place at centralised stations or hulling factories in or out of the farms, which aggregate enormous amounts of residues as mentioned above (Figure 5, 13). The most common practice worldwide involves leaving the solid residues from both crops in piles, often without any additional management, such as aeration. The anaerobic decomposition of wet residues in these enormous piles is an important source of GHG emissions, as well as soil and water contamination (San Martin Ruiz et al., 2018; 2021), if not managed properly. The primary concern revolves around the substantial CH_4 and N_2O production from the residue piles in the field (Boldrin et al., 2009; Andersen et al., 2010; Zhu-Barker et al., 2017).

The primary issue with coffee and cocoa residues is that usually they are left in piles until the following season when they might be returned to the field as a source of nutrients. In these conditions, high emissions of CH_4 and N_2O are expected, especially of CH_4 due to the anaerobic conditions inside the piles (Table 2 and Figure 14) (San Martin Ruiz et al., 2018). Leave organic residues without proper management can exacerbate environmental problems and contribute to increased GHG emissions (Andersen et al., 2010; Zhu-Barker et al., 2017; San Martin Ruiz et al., 2020; 2021). Accounting for these emissions in the life cycle assessment of the C footprint of coffee and cocoa is mandatory, as the management used to treat the organic residues produced can potentially increase emissions even further (San Martin Ruiz et al., 2018).

GHG emissions are not the only concern associated with improper treatment. Emissions of NH_3 and volatile organic compounds (VOCs) during organic residue decomposition are particularly concerning as they serve as precursors for secondary fine particulate matter, which constitutes the primary contributor to health impacts related to air pollution (Nordahl et al., 2020). NH_3 and VOCs have low odour detection thresholds, making them malodorous. NH_3 emission also contributes to soil acidification and N deposition in sensitive natural areas, negatively affecting biodiversity (ApSimon et al., 1987; Krupa, 2003). However, little is known about NH_3 emissions from piles of coffee and cocoa residues.

It is essential to implement effective management strategies to mitigate environmental issues, such as CH_4 and N_2O emissions. One straightforward method for treating solid residues on the farm is through composting using a proper management approach. This includes aeration to decrease anaerobic conditions. The motivations for composting include: 1) reduction of CH_4 emissions: Composting helps avoid the release of CH_4 associated with anaerobic decomposition that typically occurs in solid residue rich in C and N; and 2) Production of compost (Soil conditioner/organic source of nutrients): When done properly, the compost generated is free of pathogens, and is ready for use as a soil conditioner which can enhance soil health and be a useful source of nutrients. Thermophilic conditions must occur during composting to kill pathogens; 3) compost can result in nutrient-rich soil amendments that enhance soil structure, water retention, and nutrient availability, it can promote microbial activity and help to suppress weed growth.

Figure 14. GHG measurements from compost piles made with pulp residue from coffee production in Zambia (a, b) (Picture from Kateshi farm in Zambia, photos by Dorien Westerik).



While one of the motivations for composting organic residue is to prevent CH_4 emissions from the piles of residues, the composting process itself produces CH_4, N_2O and NH_3. However, these emissions are not yet fully understood (Nordahl et al., 2023). Further research is essential to comprehend the role of solid residues from coffee and cocoa production in GHG emissions and their impact on the overall C footprint. Additionally, the leaching of nutrients into the soil under the compost heap may also occur, especially potassium (K) (Hougni et al., 2021), however, good practices such as bedding/concrete floors to reduce leaching risks could be adopted.

4.2. Wastewater residues

The wastewater generated from coffee processing is characterized by its high BOD, reaching levels of 436 to 12500 mg L^{-1}, and a COD of 3465 to 22,000 mg L^{-1} (Tekle et al., 2015; Sengupta et al., 2020; Genanaw et al., 2021). Additionally, coffee wastewater tends to be acidic and high in nutrients; exhibiting pH values from 3.6 to 6.0 (Sengupta et al., 2020; Genanaw et al., 2021) and concentrations of N and P that vary from 109 to 350 mg N L^{-1}, and from 5.6 to 23 mg P L^{-1}. Consequently, traditional washed coffee processing units produce substantial quantities of high-strength wastewater, which is either discharged directly into water bodies or partially treated before being released into the environment (Tekle et al., 2015; Genanaw et al., 2021).

To reduce the environmental problems associated with the disposal of coffee wastewater into rivers, farmers often implement wastewater management systems, which may include sedimentation of tanks, called "settling ponds", to treat this liquid residue (Sengupta et al., 2020; Pulleman et al., 2023) (Figures 5, 6, 7). The solid material settles out, which together with continuing decomposition leads to gradual reductions in wastewater BOD from pond to pond until the water is safe to release to rivers. Proper treatment ensures that the discharged water meets environmental standards and does not harm nearby ecosystems. However, in many cases, the residue is simply released into ponds without additional treatment (Table 2), where it can remain for several months. The primary goal of this strategy is to avoid water pollution. Pollutants in the wastewater, such as organic matter, can contaminate local water bodies, decreasing the O_2 concentration, and affecting aquatic life and human health (Genanaw et al., 2021).

One of the main problems associated with this type of management, which involves ponds without additional treatment, is the issue of GHG emissions, particularly CH_4, which occurs under anaerobic conditions (Yang et al., 2023). However, there is currently a lack of quantitative information in the literature describing the potential effects of coffee wastewater on GHG emissions. Some literature is available on wastewater from sugarcane production that may provide some indications for the quantitative importance of wastewater for the C footprint of a product, and the relative importance of different GHGs (Oliveira et al., 2015; Oliveira et al., 2017). Oliveira et al. (2015; 2017) conducted a comprehensive assessment of GHG emissions originating from ponds and the transport of vinasse (a liquid organic byproduct of the sugarcane biofuel industry) through open channels in Brazil. Their research revealed that the storage and transportation phase constitute a significant source of CH_4 emissions and emphasizes the importance of integrating these values into GHG inventories for sugarcane ethanol production. According to their findings, the CH_4 emission from the ponds was on average 2 g CO_{2eq} m^{-3} of vinasse, where CH_4 accounted for approximately 98% of the total GHG emissions during vinasse storage and transportation, while N_2O emissions contributed less than 2%. The study demonstrated that CH_4 emissions originate from the decomposition of organic material deposited at the bottom of channels and ponds. Similar findings were reported by Wood et al. (2014), who observed that aged liquid dairy sediments function as an inoculum/source for CH_4 production. They also found that removing these sediments from the bottom of tanks resulted in a 56% reduction in CH_4 emissions. Thus, the removal of sediments from the bottom of channels and tanks can be an effective strategy for mitigating CH_4 emissions (Wood et al., 2014; Carvalho et al., 2017), with the composting process of the residues later. Another option is to aerate the system, to create aerobic conditions (Yang et al., 2023). Yang et al. (2023) showed that aeration in aquaculture ponds decreased CH_4 emissions by 41% but increased N_2O emissions by 50%. Despite the higher N_2O emissions in aerated ponds, the total global warming potential of the GHGs was 40% lower in aerated ponds because CH_4 accounted for >90% of the CO_2 equivalent. This shows that it is essential to include both CH_4 and N_2O emissions resulting from coffee wastewater storage and transportation in life cycle analyses conducted for coffee and cocoa production.

5. Greenhouse gas monitoring during composting and wastewater treatment

In addition to the existing knowledge gap regarding GHG emissions from coffee and cocoa composting and, especially, from wastewater ponds, there is also a lack of recommended techniques to measure such gases under these conditions. However, many methods are used to quantify GHG emissions from composting and wastewater in other sectors, each with its set of advantages and disadvantages (Tables 3, 4). Emissions can be studied through controlled laboratory experiments and in-situ field measurements. Emissions can be measured at a single time point or over longer periods to capture seasonality, at one spot or along several points along the composting pile (windrow) or ponds. Field measurements can be conducted continuously using on-site gas analyzers or intermittently by collecting samples for subsequent laboratory analysis. The choice of spatial and temporal resolution depends on the specific sampling conditions and the objectives of the study. Apart from emission measurements, intermittent assessment or continuous monitoring of conditions within composting piles or wastewater ponds, such as oxygen levels, temperature, moisture levels and C:N ratios, can offer valuable insights into the mechanisms influencing emissions over time and space.

5.1. GHG emissions measurements from compost piles

Measurements can be carried out in the field during pilot experiments under relatively controlled conditions or at full scale, simulating typical composting conditions. Ideally, field measurements should cover the entire surface of the pile, span the complete duration of the composting cycle, and not interfere with the normal composting process. However, achieving this ideal measurement approach can be challenging in many sampling scenarios. Several sampling methods have been utilized for field measurements, including flux chambers, wind tunnels, open emission chambers, gas probes, tracer gas releases, micrometeorological mass balance, and inverse dispersion analysis. It is important to note that each approach comes with its own set of limitations (Table 3, Annex 1), as described below.

5.1.1. Measurement approach

Flux Chambers

One of the most common methods involves using static chambers, which have a relatively small surface area compared to the entire composting pile (windrow) (Figure 15) (Andersen et al., 2010; Kumar et al., 2011; Zhu-Barker et al., 2017). Chambers assess gas emissions by positioning an open-bottomed chamber on the sampling surface and measuring gas accumulation in the chamber's headspace over a brief period (Rochette and Eriksen-Hamel, 2008; Charteris et al., 2020; Clough et al., 2020; Grace et al., 2020). Daily gas fluxes are usually estimated from chamber measurements taken once a day. Spatially and temporally integrated cumulative emissions are determined from daily flux measurements taken from several replicate chambers at specific intervals throughout the entire experimental period, which typically spans a few months (de Klein et al., 2020). Researchers adopt varied flux chamber methodologies based on the specific goals of their measurements, such as analysing landscape trends, evaluating treatment differences, or measuring emission factors for inventory purposes (Rochette and Eriksen-Hamel, 2008). Even projects with similar aims can differ in methodologies due to variations in chamber design, deployment frequency, type of analyser used for the quantification of gas concentrations, and data processing techniques.

There is also more than one possible way to sample gases. When using flux chambers, the limited surface area may not fully represent the entire pile, necessitating the use of more chambers. Consequently, this may constrain the measurement resolution. Additionally, the chamber can introduce pressure and concentration gradients that impact emission fluxes from the pile surface (de Klein et al., 2020). These methods are suitable for quantifying gaseous emissions from sources with homogeneous emissions.

Figure 15. Greenhouse gas sampling using static chambers in compost piles made with residue from coffee production in Zambia (a, b) (Picture from Kateshi farm in Zambia, photos by Dorien Westerik).

Wind Tunnels

Wind tunnels serve as an alternative to flux chambers, especially in conditions with high water vapours (Figure 16a). These tunnels are static with open bottoms and feature a fan to homogenize the air inside, introducing ambient air to the emitted gases (Kumar et al., 2011). Unlike flux chambers, wind tunnels cover larger surface areas and offer better control over the water content in GHG samples due to air dilution. However, like flux chambers, samples taken from wind tunnels might not fully represent the entire pile due to the limited surface area sampled. To calculate emission flux accurately, GHG concentrations inside and outside the tunnel must be simultaneously sampled since ambient air with non-zero concentrations of the target gases is used for dilution.

Open Emission Chambers

The open emission chamber captures GHG emissions from the emitting surface of the pile, with one of its walls open to allow natural or facilitated airflow in and out (Amon et al., 2001; Fukumoto et al., 2003). This airflow can be natural or facilitated by ventilation. Theoretically, this sampling approach should not significantly alter the conditions inside the chamber. However, it is crucial to note that the studied pile may not entirely represent field conditions. Moreover, this method does not enable the differentiation of emissions across the pile's surface area. Precise control of the airflow through the chamber is necessary for accurate measurement of emissions with this method. For more information see Amon et al. (2001) and Fukumoto et al. (2003).

Figure 16. An example of gas probe collection from the compost pore space (a) and wind tunnel in a composting pile (windrow) made with pig manure in the south of Brazil (b) (Photos by Késia .S. Lourenço).

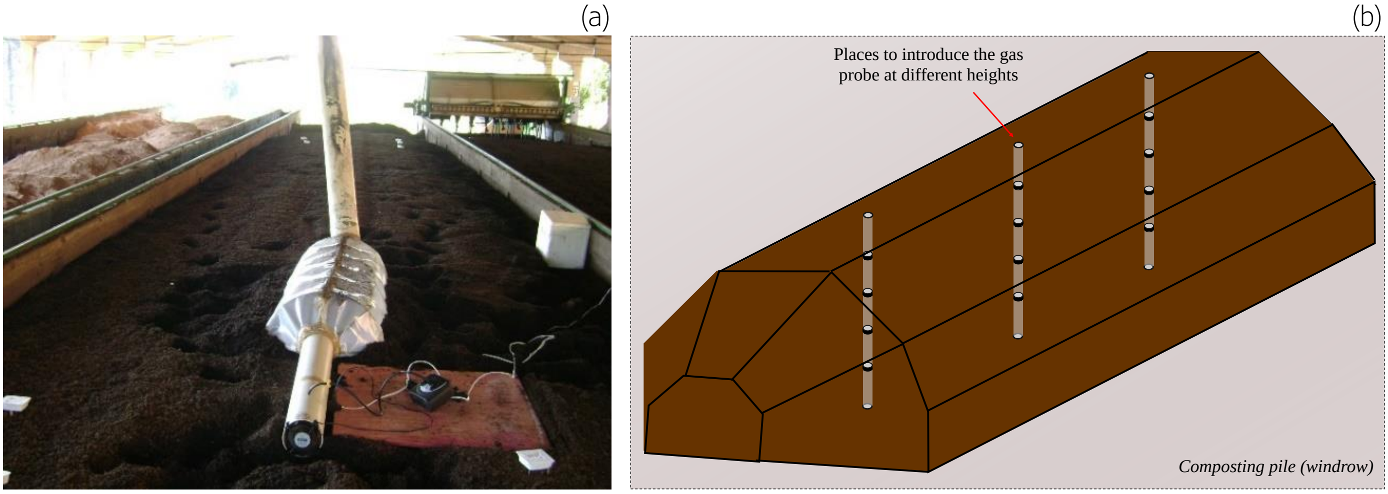


Table 3. Advantages and disadvantages of the main greenhouse gas sampling methods for compost piles found in the literature.

MEASUREMENT APPROACH	ADVANTAGES	DISADVANTAGES	ATTENTION POINTS
Flux Chambers	1. Relatively inexpensive, easy to adopt, versatile, and adaptable to varying conditions. 2. Suitable for quantifying gases from sources with homogeneous emissions. 3. Enables differentiation of emissions across the pile's surface area. 4. The system can be used with automatic chambers or manual sampling. 5. GHG sampling can be done over time using chambers, with or without a fan. 6. Gases can be analysed using gas chromatography (GC) or real-time gas analysers. 7. Suits experiments where treatments are compared in replicates, allowing for statistical analysis. 8. Suits both laboratory and field experiments.	1. Small surface area measured relative to the size of the composting pile. 2. Chambers can induce pressure and concentration gradients that impact emission fluxes from the pile surface. 3. Gas measurement is not conducted continuously, but done intermittently over a specified period and area. 4. Time and labor-consuming. 5. Can underestimate emissions from full-scale composting plants.	• Accumulation of the specific gas within the chamber headspace might lower the concentration gradient between the sampling area and the air, potentially reducing the flux. This challenge can be addressed by employing alternative models (rather than linear models) to calculate the flux. • For manual chambers only, the intermittent, event-based sampling approach should be used. Consequently, there is a risk of missing high peaks.
Wind Tunnels	1. Serve as an alternative to flux chambers, especially in moist conditions like steam. 2. Cover larger surface areas than flux chambers, and offer better control over the water content in GHG samples due to air dilution. 3. Gases can be analysed using real-time gas analysers. 4. Suitable for laboratory and field experiments.	• Emission do not represent the entire pile due to the limited surface area sampled. • Tunnels have open bottoms and feature a fan to homogenize the air inside, diluting the gases emitted by the pile with ambient air. To calculate emission flux accurately, GHG concentrations inside and outside the tunnel must be simultaneously sampled and corrected for. • The measurement of gases is not continuous; it is done intermittently over a specified period and area. • Needs to follow the event-based sampling approach. Based on this, high peaks can be missed due to the lack of sampling. • It is a time-consuming technique. • Can underestimate emissions from full-scale composting piles. • Controlling airspeed can be challenging, and variations between tunnels may lead to differences in calculated emissions.	• Demands for accurate concentration analyses, as the gas does not accumulate in the headspace as it does in closed chambers. The equipment needs to have high sensitivity.
Open Emission Chambers	1. The open emission chamber captures GHG emissions from the entire surface of the pile. 2. Theoretically, this sampling approach do not significantly alter the conditions inside the chamber. 5. Suitable for laboratory experiments.	1. Does not enable differentiation of emissions across the pile's surface area. 2. The studied pile may not entirely represent field conditions. 3. The chamber can interfere with gas fluxes by altering weather conditions. 4. Not suitable for field conditions; typically used for small piles under controlled environments.	• Precise instruments are necessary to distinguish a flux from background noise and emission.

Other methods

Various other methods can be used to quantify GHGs, such as tracer releases, inverse dispersion analysis, high-density spot sampling, and micrometeorological mass balance (Czepiel et al., 1996; Sommer et al., 2004; Scheutz et al., 2011; Hrad et al., 2014; Mønster et al., 2014; Chen et al., 2015; Kent et al., 2019). However, these methods are not particularly well-suited for quantifying GHG emissions in coffee and cocoa compost production, they are used more at larger spatial scales (identifying regional sources) (Annex 1). Follow a brief explanation about each one of them:

Gas Probes:

•Gas probes are utilized to sample gases from within the piles, providing a more comprehensive analysis beyond surface emissions (Czepiel et al., 1996; Andersen et al., 2010; Chen et al., 2015). Probes are inserted into the pile at various depths, allowing the determination of spatial gas concentration distributions within the windrow (Figure 16b). This method provides insights into composting dynamics, such as regions with anaerobic activity and elevated gas concentrations. It is crucial to understand that gas probes measure potential emissions, not necessarily direct releases into the atmosphere. However, emissions are what ultimately matter for climate change.

Tracer Releases:

•Tracer Releases involve releasing a known quantity of a trace gas, like sulphur hexafluoride, into the environment. By tracking its dispersion and concentration downwind, researchers estimate emission rates of other gases, including GHGs. While useful for large-scale studies, it may not be necessary for smaller composting operations (Hrad et al., 2014).

Inverse Dispersion Analysis:

•Another approach to quantify total emissions from a full-scale composting plant involves utilizing an inverse dispersion technique. It is a method employed to estimate emission rates from a particular source. This technique involves measuring gas concentrations downwind from the source, coupled with meteorological information, and using mathematical models to calculate the emission rates in reverse (Hrad et al., 2014). This approach is based on atmospheric dispersion principles, where pollutants disperse and dilute as they are carried by the wind. By examining concentration gradients in the atmosphere downwind of the source, researchers can deduce the emission rates of pollutants from the source. While it is valuable for some emission studies, its relevance to coffee and cocoa compost production may be limited due to the specific nature and scale of these operations. These techniques are used more on larger scales in or to identify regional sources.

Micrometeorological Mass Balance:

•This method calculates emissions based on measurements of wind speed and gas concentrations at multiple points within an area. The method is used to estimate emissions from a specific area or source (Sommer et al., 2004; Kent et al., 2019). It is often used for larger agricultural operations or industrial sites. In smaller-scale coffee and cocoa composting operations, simpler methods are better for GHG quantification. The basic principle involves measuring the gas concentration downwind from the source and calculating the mass of gas passing through a defined cross-section of the plume. This calculation considers factors such as wind speed, direction, the area of the cross-section, and the measurement duration. By integrating these variables, researchers can estimate the total mass of the emitted gas. The assumption is that emissions arise from a homogeneous emitting field, which is not the case, since the emissions stem from a heterogenous area (i.e. compost heap inside a plantation).

Dynamic plume tracer dispersion:

•The technique combines a double tracer technique that combines controlled tracer gas release from the source with time-resolved concentration measurements downwind of the source. The tracer technique relies on the premise that a tracer released at an emission source, such as a compost pile or landfill, disperses in the atmosphere similarly to the gas of interest emitted from the same source. Under the conditions of a defined wind direction and well-mixed air above the landfill, the emission rate of the gas of interest can be calculated by comparing the integrated cross-plume concentration of the emitted gas to the integrated cross-plume concentration of the tracer (Scheutz et al., 2011). Integrated cross-plume concentration refers to the total amount of a specific substance, such as a pollutant or tracer gas, present in a defined cross-sectional area perpendicular to the wind direction. Quantification involves conducting multiple traverses perpendicular to the plume originating from the pile, simultaneously measuring the atmospheric concentration of the two gases. These measurements are taken when the wind direction allows for measurements downwind (Mønster et al., 2014).

5.1.2. High-Density Spot Sampling

Despite the methodology used, we must consider that the piles exhibit spatial heterogeneity across the emitting surface. Besides, it is not easy or practical to use open emission chambers or micrometeorological approaches to capture emissions from individual composting windrows. So, a few flux chambers, wind tunnels or gas probes' footprint approaches are not sufficient to capture a representative sample of emissions. In these cases, a high-density spot sampling method must be employed (Preble et al., 2020; Nordahl et al., 2023). Multiple chambers and piles must be sampled to compare emission rates across the composting cycle. This approach is intensive before, during, and after sampling, involving work for sampling, vial preparation, and GHG analysis.

5.1.3. Comparing different measurement methods

Nordahl et al. (2023), suggests there is no single approach among the methods compared by authors in field-based experiments that is superior. The distribution of the chambers across the pile and sampling size are the most important factors for calculating GHG cumulative emissions and emission factors. Another crucial factor is GHG sampling throughout the composting process. Commercial composting takes 3 to 6 months, and emissions vary across the mesophilic, thermophilic, and maturation phases. Therefore, GHG measurements must be taken over the entire composting cycle to determine a final emission factor.

Another important conclusion of Nordahl et al. (2023) is that there is not sufficient evidence to suggest that any particular method consistently overestimates or underestimates emission measurements more than others. There are not enough published method comparison studies to draw meaningful conclusions. Based on this, researchers must ensure that they use the right methodological approach for the GHG measurement technique selected and the study conditions (in this case compost piles) to ensure the quality of the study results. For example, for spot sample approaches, the researcher must employ a sufficiently high temporal and spatial sampling intensity.

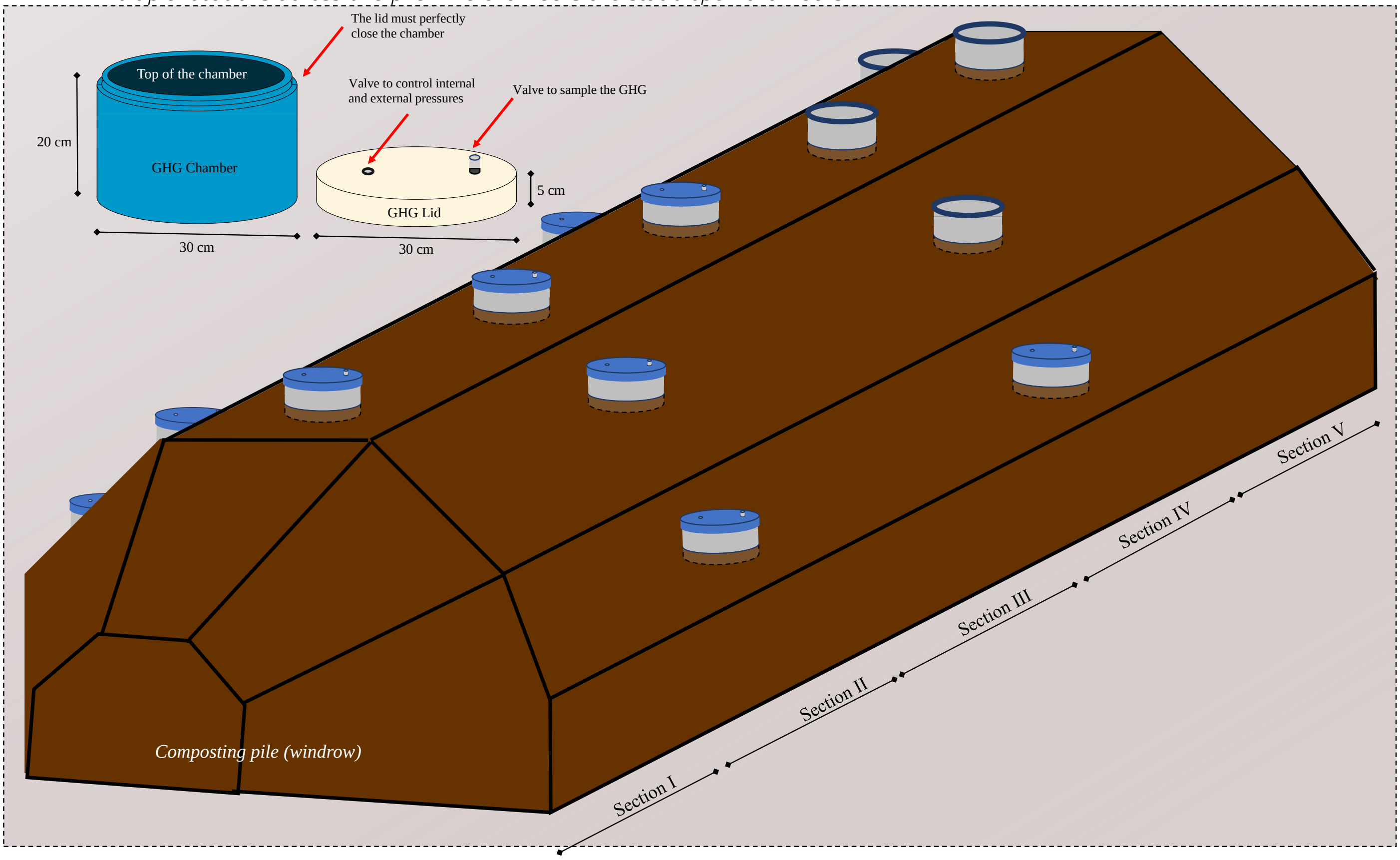
5.1.4. Proposed method for sampling GHG in composting from coffee and cocoa residues

Based on the literature review and the importance of measuring GHG emissions in field conditions, we propose using the static chambers method to quantify GHG emissions from compost piles in farms that produce coffee and cocoa (Figure 17). This method is relatively inexpensive, easy to adopt, versatile, and adaptable to varying field conditions. An additional advantage is that a similar approach is already used for soil GHG flux sampling. Thus, the same personnel conducting the experiments with coffee and cocoa fertilization have already been trained to handle GHG sampling in the compost piles. Moreover, with this technique, different treatments can be tested in different piles to define compost production strategies with the lowest GHG emissions.

Considering the specified criteria, it is proposed to employ similar GHG chambers in the compost piles (windrow) as those utilized in experiments assessing the impact of mineral and organic fertilization on GHG production and emissions in the atmosphere. These chambers will be systematically positioned throughout the entire pile, ensuring comprehensive GHG sampling during the composting period, which typically spans 3-6 months (Figure 17). Initially, the chambers will be installed and retained in position until the compost windrow is turned (if such a step becomes necessary). During the turning process, GHGs must be sampled both before and after the event to capture potential emission bursts. The chambers must be installed in a vertical position (90-degree angle) across the windrow to prevent protection against rain (preventing them from acting as a shelter during rain events) (Figure 17).

Since emissions can vary within the pile, the length of the compost pile must be taken into account to determine the number of chambers. Depending on the size of the pile, during each sampling event, samples must be collected in different locations. For example, in piles of 100 m in length, we recommend that 15 chambers be installed. This is achieved by first dividing the windrow into five sections (Sections I–V) (Figure 17). In each section, three open chambers will be located on the top, upper side, and lower side of the pile. The chambers will be installed at least one meter from the end of the pile to ensure that the measurements represent the pile emissions. The emission in the area of the pile varies depending on the position, Andersen et al. (2010) showed that the majority of windrow emissions are emitted from the top of the pile. Based on this, researchers must consider placing chambers in different positions on the pile sides and account for the area that these emissions represent. It is worth mentioning that there is no information in the literature about the minimum number of chambers required per linear or square meter of the pile, research on this topic is necessary. The experience of the researchers will also help to define the best distribution of the chambers.

Figure 17. Composting pile (windrow) with GHG chambers installed in different locations. The goal is to sample the GHG emitted from multiple locations across one pile. The chambers are static open chambers.



The chamber closure time, as well as the number of samples per chamber and sampling event, must be predefined to calculate gas fluxes, with a recommended minimum of three samples per chamber depending on the equipment used. A long chamber closure time, such as one hour, can create pressure and concentration gradients that affect emission fluxes from the pile surface but might be necessary as different gases might show considerable differences in flux intensities (e.g. low N_2O flux, high CH_4 flux). The resulting significant accumulation of specific gases like CH_4 and water vapours in the chamber headspace might decrease the concentration gradient between the sampling area and the air. However, non-linear models for the calculation of the flux can overcome these limitations (Hüppi et al., 2018).

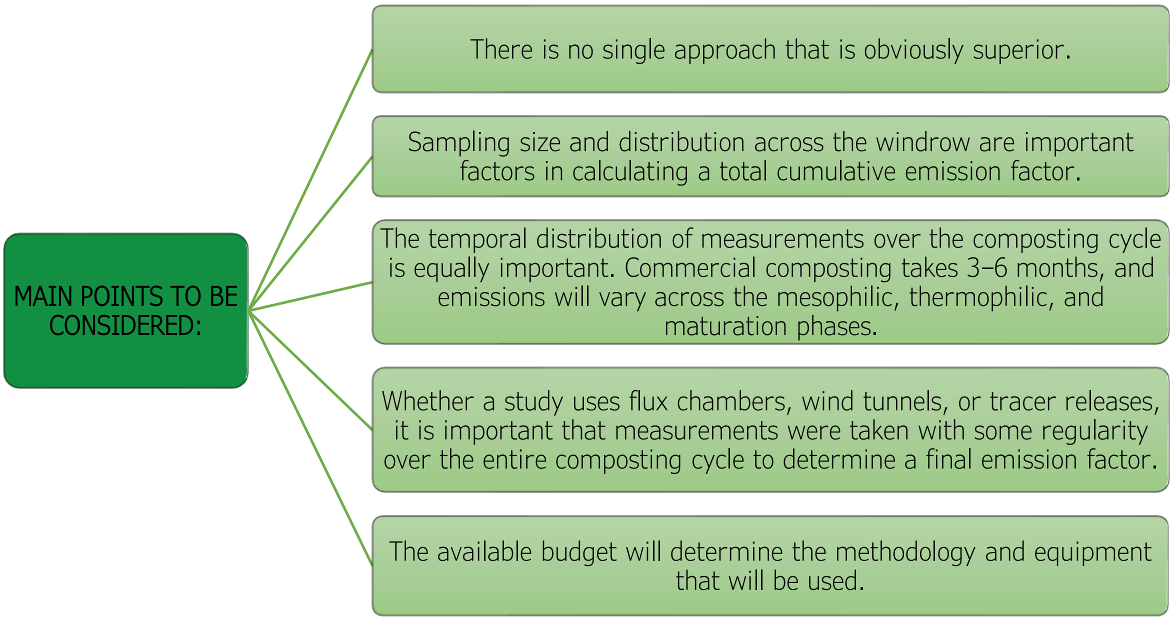
The suggested protocol involves collecting gas samples before (on the day of turning) and after (<1 h) the pile turning (Zhu-Barker et al., 2017). During the biweekly turning period, gas samples will be collected once between the two contiguous turning days. After that, sampling can be done once or twice per week. For instance, following the sampling event approach mentioned earlier, at least 50 sampling events will be carried out per windrow over approximately 6 months, equivalent to around 180 days, with GHG samples taken twice per week. In the ideal scenario, samples of compost for determining mineral N (NH_4^+ + NO_3^-) concentration, pH, moisture and, possibly, oxygen concentrations should be collected at each gas sampling event, together with temperature measurements. However, this is contingent on the availability of resources and the laboratory's capabilities. Oxygen concentrations, available N and temperature are crucial variables that influence GHG emissions. Turning the pile would significantly alter these variables.

To calculate the percentage of C and N lost as CH_4 and N_2O (emission factor), it is crucial to determine the amount of C and N added as raw material and lost as gas (CH_4 and N_2O) throughout the entire process. For this purpose, the new piles need to be weighed using a truck scale, with measurements taken both before and after the composting process. Additionally, the total C and total N content of both the raw and composted material must be determined. All the materials added to form the pile must be weighed, and their concentrations of C and N need to be known to calculate their loss accurately.

Various methodologies and equipment can be employed to measure GHG concentrations. The methodologies can be distinguished in discrete sampling (using gas chromatography - GC) and gas measurements using field-deployable gas analysers provided by several companies (Innova, PICARRO, ABB-Los Gatos Research, LI-COR, AERIS), each with its advantages and specific technologies (Maier et al., 2022). The principle of GC is to separate gases based on their chemical properties and affinity for a stationary phase within a column, and then quantify each separated component. GC is a versatile technique with high precision and accuracy, suitable for a wide range of gases, and is often used in research and environmental monitoring (Maier et al., 2022). However, it is a time-consuming technique, requires skilled operators, and may not be suitable for continuous real-time monitoring. Gas analysers typically employ absorption spectroscopy, utilizing laser light to precisely measure the absorption features of gases (Maier et al., 2022). It is a sensitive technique, suitable for trace gas detection, and can provide real-time measurements. However, their sensitivity can be affected by environmental conditions such as ambient temperature and cross-interference by other gases. Thus, different measures have to be taken (e.g. use of chemical traps) to overcome these problems. Such instruments are costly initially, but the investment may be back within a short period due to the savings in avoided downstream analytical costs. However, maintaining a backup instrument is recommended in case of breakdowns, as sending an instrument for repairs to the manufacturer can take several months. In theory, all of them can be used to quantify GHG emissions in compost piles (Nicoloso et al., 2013). However, before deciding on the technique, tests must be conducted. There are also other aspects to consider, such as costs, required labour, and sampling methods. For instance, a less accurate analysis but with more measurements will give a more accurate estimate of emissions, considering the large temporal and spatial variability.

The choice of method depends on the specific requirements of the application, including the gases to be measured, required accuracy, response time, and budget constraints (Figure 18). GC typically offers higher accuracy, while gas analysers provide real-time data with slightly lower accuracy but higher precision. Whereas GC requires sample collection and processing, making it slower. GC is highly sensitive and suitable for trace gas analysis while Gas Concentration Analysers vary in sensitivity depending on the specific technology used. Based on this, before choosing the equipment, the goal of the research must be determined.

Figure 18. Main points to be considered during the development of projects related to tracking the fluxes of different gases in compost piles.



MAIN POINTS TO BE CONSIDERED:

There is no single approach that is obviously superior.

Sampling size and distribution across the windrow are important factors in calculating a total cumulative emission factor.

The temporal distribution of measurements over the composting cycle is equally important. Commercial composting takes 3–6 months, and emissions will vary across the mesophilic, thermophilic, and maturation phases.

Whether a study uses flux chambers, wind tunnels, or tracer releases, it is important that measurements were taken with some regularity over the entire composting cycle to determine a final emission factor.

The available budget will determine the methodology and equipment that will be used.

5.2. GHG emissions measurements from wastewater ponds

The procedures described below are intended to assess the flux of CH_4 and N_2O from coffee processing wastewater. Most of the available studies were conducted in natural ponds, human-treated wastewater, or fishing ponds (Duchemin et al., 1999; Silva et al., 2015; Enström et al., 2019; Audet et al., 2020; Ho et al., 2021; Zhao et al., 2021; Malyan et al., 2022). Scarce information is known about GHG emissions in coffee wastewater. Typically, GHG emissions from ponds and lakes are measured using common techniques like 'floating chambers (similar to static soil chambers)', or via the dissolved gas concentration of which the flux to the atmosphere is inferred. The utilization of eddy covariance towers is not common due to their high cost and the requirement for specialized technicians for installation and operation (Zhao et al., 2021). Besides, eddy covariance is rarely used to measure emissions from rivers or small wastewater ponds as it needs a quite large homogenous fetch -depending on the height of the tower several hundred meters around the tower (Annex 1) (Kumar et al., 2021; Zhao et al., 2021). These techniques possess both advantages and limitations in terms of spatial and temporal coverage, as well as accuracy in capturing GHG flux (Table 4). The methods can be split into two major types (Lambert and Fréchette, 2005):

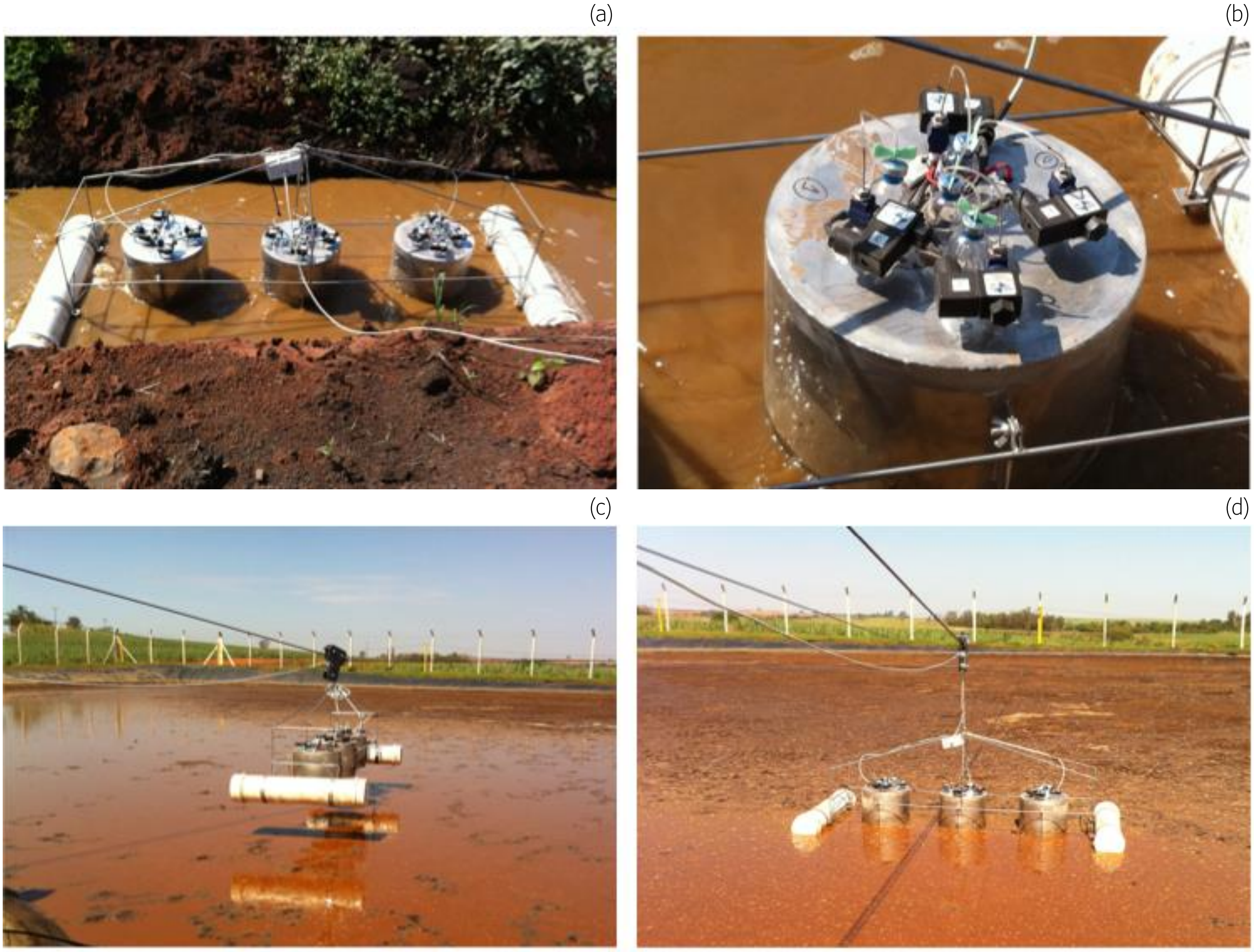
a) Fluxes calculated by measuring the GHG across the air-water interface: floating chambers.
b) Fluxes can be calculated by measuring the dissolved concentration of GHG in the water directly. This can either be done using the headspace equilibration technique or specialized probes for water concentration measurements. Using the gas transfer velocity the flux from water to the atmosphere can be calculated subsequently.

5.2.1. Measurement approach

Floating flux chambers

The floating chamber operates on the same principle as flux chambers utilized for sampling gases from soils or compost piles (Ye et al., 2014; Pan et al., 2016; Bellandi et al., 2017; Caniani et al., 2019). The chamber is open at the bottom and configured in a way that enables it to float on the water (Figures 19, 20). The floating chamber technique is a standard technique to measure diffusive GHG fluxes from aquatic systems (Duchemin et al., 1999; Silva et al., 2015; Enström et al., 2019; Audet et al., 2020; Ho et al., 2021; Zhao et al., 2021; Malyan et al., 2022). These chambers come in various sizes and shapes tailored to specific conditions and project needs. As done for static chambers used on soil surfaces or compost heaps, concentration increases over time and can be determined using either discrete manual sampling or methods via laser spectroscopy.

Figure 19. Automatic greenhouse gas sampling units deployed in vinasse transportation systems (a, b) and vinasse storage ponds (c, d). It is worth mentioning that, in this case, the temperature of the liquid inside the pond averaged 100°C. Source: Oliveira et al. (2017).



Headspace equilibration method: Calculating fluxes from wastewater based on dissolved concentrations

The flux from wastewater to the atmosphere can also be determined indirectly by measuring the concentration difference between the gases dissolved in the wastewater pond and the atmosphere given the gas transfer velocity is known. The headspace equilibration technique is probably the most widely employed method for determining the dissolved gas concentration in water, valued for its simplicity, reliability, and suitability for routine sample analysis (Jahangir et al., 2012). There are several adaptations of this method in the literature. Another way to determine the dissolved concentrations is spray equilibrators used in combination with analysers. In this method, water is being pumped through a spray equilibrator thereby forcing the gas out of the solution. The gas concentration is then measured directly in the headspace of the surrounding enclosure. Lastly, there are a few companies (Pro-Oceanus, Eosense) which manufacture in-situ probes for the direct quantification of CH_4 or CO_2 in solution. However, these probes are relatively expensive.

Figure 20. *Floating flux chambers (Photos by Matti Barthel).*

Gas Ebullition

In aquatic systems, the so-called ebullition flux can occur next to the diffusive flux. Ebullitive fluxes are spontaneous emissions caused by bubbles formed in the sediment of the respective system. Because of their erratic nature, ebullitive fluxes are usually measured over a longer period time (hours to days) using either submerged inverted funnels or floating chambers anchored to the ground to remain at the same spot (Walter et al., 2008; DelSontro et al., 2016). After a set period, the funnels are removed with care, and the trapped gases are collected for analysis, typically employing techniques such as GC or infrared spectroscopy. The dimensions of the inverted funnel should be determined according to the rate of bubble emission. The funnel must be fully submerged, and any pre-existing air should be eliminated before initiating the sampling process. Prior to conducting GHG sampling and analysis using this approach, it is essential to verify that there is no water flow and the pond's bottom slope is less than 20 degrees. These conditions guarantee the stability of the sampling system over an extended period and minimize procedural errors.

This funnel technique needs to be deployed alongside the measurement with floating chambers to distinguish between ebullitive and diffusive emissions.

Table 4. Advantages and disadvantages of the main greenhouse gas sampling methods from wastewater ponds, water bodies, and lakes. Note that gas ebullition is a specific measurement approach which is only conducted when ebullitive fluxes are to be expected from the system (high GHG production in the sediment).

MEASUREMENT APPROACH	ADVANTAGES	DISADVANTAGES	ATTENTION POINTS
Floating flux chambers	1. Easy to apply, can be used in a wide range of experiments. 2. Enables differentiation of emissions across the pond surface area. 3. Can be used with automatic chambers or for manual sampling. 4. GHG sampling can be done over time. 5. Gases can be analysed using gas chromatography (GC) or real-time gas analysers like Photoacoustic Gas Monitor (INNOVA) and Gas Concentration Analyser (Picarro). 6. Suitable for quantifying gaseous emissions from sources with homogeneous emissions. 7. Relatively inexpensive, easy to adopt, versatile, and adaptable to varying conditions. 8. This technique allows simultaneous measurement of CO_2, CH_4, and N_2O fluxes	1. Small surface area relative to the size of the pond. 2. The chamber can introduce pressure and concentration gradients that impact emission fluxes from the pond surface, potentially lowering the flux. 3. The measurement of gases is not conducted continuously; but intermittently over a specified period and area. 4. High peaks can be missed due to the event-based sampling approach. 5. Time and labour-demanding. 6. Can underestimate emissions from full-scale pond plants.	• Gas flow calculations assume a linear increase in headspace concentration, but this assumption mainly fails due to fluctuating gas exchange caused by non-steady-state conditions in closed static chambers, resulting in underestimated GHG fluxes. This can be overcome by non-linear models.
Gas Ebullition	**1.** Easy method, can be used in a big range of experiments. **2.** Enables differentiation of emissions across the pond surface area. **3.** Gases can be analysed using gas chromatography (GC) or real-time gas analysers like Photoacoustic Gas Monitor (INOVA) and Gas Concentration Analyser (Picarro). **4.** It is relatively inexpensive, easy to adopt, versatile, and adaptable to varying conditions. **5.** This technique allows simultaneous measurement of CO_2, CH_4, and N_2O fluxes	1. No water flow is allowed, and the pond's bottom slope should be less than 20 degrees. 2. The gas content in the bubbles tends to be highly variable between systems and even between sites of a single system, thereby potentially masking any underlying relationships between bubble production and environmental variables. 3. Small surface area compared to the entire pond. 4. The gas measurement is not conducted continuously; it is done intermittently over a specified period and area. 5. Time and labor-intensive. 6. Can underestimate emissions from full-scale ponds plants.	

Continuation...

MEASUREMENT APPROACH	ADVANTAGES	DISADVANTAGES	ATTENTION POINTS
Headspace equilibration method	1. Easy method, can be used in a big range of experiments. 2. Enables differentiation gas concentration across the pond surface area. 3. Water sampling can be done over time. 4. Gases can be analysed using gas chromatography (GC) or real-time gas analysers like Photoacoustic Gas Monitor (INOVA) and Gas Concentration Analyser (Picarro). 5. Suitable for quantifying gaseous from sources with homogeneous emissions. 6. Relatively inexpensive, easy to adopt, versatile, and adaptable to varying conditions. **6.** Allows simultaneous measurement of CO_2, CH_4, and N_2O fluxes	1. Measures potential emissions, not necessarily direct releases into the atmosphere. 2. Small surface area compared to the entire pond. 3. The water is sampled in small containers and the gas is subsequently analysed, not under real field conditions. 4. The measurement of gases is not conducted continuously; it is done intermittently over a specified period and area. 5. Needs to follow the event-based sampling approach. Based on this, high peaks can be missed due to the lack of sampling. 7. Can underestimate emissions from full-scale pond plants.	

5.2.2. Proposed method for sampling GHG in coffee wastewater treatment ponds

Based on the literature review and the importance of measuring GHG emissions in field conditions, we propose using the floating chambers method to quantify GHG emissions from coffee wastewater. This method is relatively inexpensive, easy to adopt, versatile, and adaptable to varying field conditions. This approach is similar to the one that is recommended for soil and compost pile sampling so the same personnel conducting experiments with coffee and cocoa fertilization and composting have already been trained to handle GHG sampling in the ponds. In addition to the floating chamber measurements, we propose incorporating the headspace equilibration technique to measure dissolved gas concentrations. Simultaneous measurements of surface fluxes and dissolved gas concentrations enable the determination of gas transfer velocity in wastewater ponds. This information allows the calculation of water-to-atmosphere fluxes based solely on dissolved concentrations. The straightforward nature of measuring dissolved gases facilitates an increase in sampling frequency through the combined use of both approaches.

The first step involves the careful selection of sampling points within the coffee wastewater treatment ponds. These points should be representative of the entire system, considering variations in water flow, temperature, and other environmental factors. The number of chambers will vary depending on the size of the pond. Figure 19 shows a possible model to be applied, utilizing automatic floating chambers with three replicates. However, it is also possible to install separate chambers in different positions in the pond (Figure 20). The chambers are left in place for specific durations allowing gases to accumulate. The closure time of the chambers depends on the system and can be relatively short if fluxes are very high. Following the recommendations for compost piles, it is essential to conduct preliminary tests to determine and define the appropriate chamber closure time in advance. An extended chamber closure time, such as one hour, can create pressure and concentration gradients that affect emission fluxes from the pond surface. These chambers will be systematically positioned throughout the entire pond on each sampling day. Regular monitoring is necessary to ensure comprehensive GHG sampling during the wastewater treatment period, preferably at intervals reflecting temporal GHG emission patterns. Special attention needs to be given to factors such as wind speed to ensure accurate measurements.

It is necessary to follow the sampling event approach. Based on this, it is recommended to conduct a higher number of sampling events from the beginning of the harvest season onwards, especially right before and after the addition of new fluids in the ponds. It is expected that the high organic C content will increase the emissions of CH_4 and N_2O from the ponds. Additionally, the movement of liquid with each new batch can influence emissions. After that, sampling can be conducted once or twice per week. Besides, rain events can also affect the emissions. During each sampling event, it is recommended to measure the physico-chemical attributes of the wastewater, including temperature, redox potential (Eh), pH, and C and N content. Additionally, measuring oxygen concentration, BOD and COD at each gas sampling event is advisable. Oxygen concentrations, available C and N, and temperature are crucial variables that influence GHG emissions, and aeration of the wastewater would significantly alter these variables.

It is also possible to calculate the percentage of C and N lost as CH_4 and N_2O (emission factor). For this, it is crucial to determine the amount of C and N added as raw material and lost as gas (CH_4 and N_2O) throughout the entire wastewater treatment process. To do this, the total amount of liquid and the concentrations of C and N must be determined accurately. Various methodologies and equipment can be employed to measure GHG concentrations, for detailed information about each method, please refer to section 5.1.4.

By adhering to this proposed method, researchers can conduct systematic and reliable assessments of GHG emissions in coffee wastewater treatment ponds, contributing significantly to both scientific knowledge and environmental sustainability efforts.

6. Conclusions

In this report, the residues produced during post-harvest processing of coffee and cocoa have been described, as well as their environmental challenges linked to the most common management methods used by farmers around the world. By examining the characteristics of the residues, common practices adopted by producers worldwide, their impact on GHG emissions (specifically CH_4 and N_2O), and the methods for measuring GHGs, this report aims to shed light on how the coffee and cocoa industries can move towards greater sustainability, especially reducing their impact on climate change.

In summary, the dry residues generated in coffee and cocoa production are often left on the farm in piles without proper management, leading to high GHG emissions, especially CH_4. Similarly, in farms that use water, wastewater is typically left in ponds without additional treatment. Although poorly quantified, high GHG emissions are expected to occur in such circumstances. Further research is essential to understand the role of compost piles and wastewater ponds in GHG production and their impact on the overall C footprint of coffee and cocoa production. Studying the entire life cycle of coffee and cocoa industry products, including residue management practices, is crucial for developing sustainable solutions and reducing environmental impact. Additionally, various methods can be employed to treat coffee and cocoa residues, as discussed in Sections 2.3 and 3.3. For solid residues, a proper composting process with aeration can be a simple and suitable solution. Similarly, systems used for aerated fishing ponds can be adapted for treating wastewater, thereby reducing CH_4 emissions. However, the reduction potential of residue treatment methods is also poorly quantified.

The assessment of GHG emissions from piles and wastewater ponds, which are the main methods used by farmers to treat residues, involves several considerations. Firstly, there is no one-size-fits-all approach; the choice of methodology depends on various factors. Secondly, the sampling size and distribution across piles and ponds play a crucial role in accurately calculating total cumulative emission factors. Thirdly, the temporal distribution of measurements throughout the composting and wastewater cycle is vital. Given the diverse phases of composting, such as mesophilic, thermophilic, and maturation, emissions can vary significantly during each phase; therefore frequent measurements over a long period (i.e. several months) are necessary. In wastewater ponds, the emissions will vary based on the concentration of organic material, especially C and N added in the ponds. Whether using flux chambers, wind tunnels, tracer releases, or inverted funnel technic, regular measurements across the entire cycle are imperative for determining a reliable final emission. Lastly, the methodology and equipment selected are influenced by the available budget, emphasizing the importance of aligning resources with research goals. Comprehensive consideration of these key points for specific research purposes enhances the accuracy and reliability of GHG emission assessments in composting and wastewater management.

Considering the available methods and criteria mentioned above, it is proposed to use the static chamber method to quantify GHG emissions from compost piles and the floating chamber method in combination with the headspace equilibration method for wastewater. It is proposed to employ similar GHG chambers as those utilized in experiments assessing the impact of mineral and organic fertilization in the field. This method is relatively inexpensive, easy to adopt, versatile, and adaptable to varying field conditions. Moreover, utilizing these techniques allows for comparing different treatments across multiple piles and ponds, which aids in defining strategies to reduce GHG emissions during compost production and wastewater treatment. Furthermore, the same personnel conducting experiments with coffee and cocoa fertilization can handle GHG sampling in the compost piles and ponds. As mentioned before, while there is no perfect method for measuring GHG fluxes from compost and water bodies, the flux chamber method is considered the most reliable and flexible in terms of logistics.

References

Acosta, N., De Vrieze, J., Sandoval, V., Sinche, D., Wierinck, I., Rabaey, K., 2018. Cocoa residues as viable biomass for renewable energy production through anaerobic digestion. Bioresource Technology 265, 568-572. https://doi.org/10.1016/j.biortech.2018.05.100

Alemayehu, Y.A., Asfaw, S.L., Tirfie, T.A., 2020. Management options for coffee processing wastewater. A review. Journal of Material Cycles and Waste Management 22, 454-469. https://doi.org/10.1007/s10163-019-00953-y

Alves, R.C., Rodrigues, F., Antónia Nunes, M., Vinha, A.F., Oliveira, M.B.P.P., 2017. Chapter 1 - State of the art in coffee processing by-products, In: Galanakis, C.M. (Ed.), Handbook of Coffee Processing By-Products. Academic Press, pp. 1-26.

Amon, B., Amon, T., Boxberger, J., Alt, C., 2001. Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutrient Cycling in Agroecosystems 60, 103-113. https://doi.org/10.1023/A:1012649028772

Andersen, J.K., Boldrin, A., Samuelsson, J., Christensen, T.H., Scheutz, C., 2010. Quantification of greenhouse gas emissions from windrow composting of garden waste. Journal of Environmental Quality 39, 713-724. https://doi.org/10.2134/jeq2009.0329

ApSimon, H.M., Kruse, M., Bell, J.N.B., 1987. Ammonia emissions and their role in acid deposition. Atmospheric Environment 21, 1939-1946. https://doi.org/10.1016/0004-6981(87)90154-5

Asfaw, E., Nebiyu, A., Bekele, E., Ahmed, M., Astatkie, T., 2019. Coffee-husk biochar application increased AMF root colonization, P accumulation, N_2 fixation, and yield of soybean grown in a tropical Nitisol, southwest Ethiopia. Journal of Plant Nutrition and Soil Science 182, 419-428. https://doi.org/https://doi.org/10.1002/jpln.201800151

Audet, J., Carstensen, M.V., Hoffmann, C.C., Lavaux, L., Thiemer, K., Davidson, T.A., 2020. Greenhouse gas emissions from urban ponds in Denmark. Inland Waters 10, 373-385. https://doi.org/10.1080/20442041.2020.1730680

Beg, M.S., Ahmad, S., Jan, K., Bashir, K., 2017. Status, supply chain and processing of cocoa - A review. Trends in Food Science & Technology 66, 108-116. https://doi.org/10.1016/j.tifs.2017.06.007

Bellandi, G., Porro, J., Senesi, E., Caretti, C., Caffaz, S., Weijers, S., Nopens, I., Gori, R., 2017. Multi-point monitoring of nitrous oxide emissions in three full-scale conventional activated sludge tanks in Europe. Water Science and Technology 77, 880-890. https://doi.org/10.2166/wst.2017.560

Berego, Y.S., Sota, S.S., Ulsido, M.D., Beyene, E.M., 2022. Treatment Performance Assessment of Natural and Constructed Wetlands on Wastewater From Kege Wet Coffee Processing Plant in Dale Woreda, Sidama Regional State, Ethiopia. Environmental Health Insights 16, 11786302221142749. https://doi.org/10.1177/11786302221142749

Boakye-Yiadom, K.A., Ilari, A., Duca, D., 2022. Greenhouse Gas Emissions and Life Cycle Assessment on the Black Soldier Fly (*Hermetia illucens* L.). Sustainability 14, 10456

Boldrin, A., Andersen, J.K., Møller, J., Christensen, T.H., Favoino, E., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Management & Research 27, 800-812. https://doi.org/10.1177/0734242x09345275

Campos-Vega, R., Nieto-Figueroa, K.H., Oomah, B.D., 2018. Cocoa (*Theobroma cacao L.*) pod husk: Renewable source of bioactive compounds. Trends in Food Science & Technology 81, 172-184. https://doi.org/10.1016/j.tifs.2018.09.022

Campos, R.C., Pinto, V.R.A., Melo, L.F., Rocha, S.J.S.S.d., Coimbra, J.S., 2021. New sustainable perspectives for “Coffee Wastewater” and other by-products: A critical review. Future Foods 4, 100058. https://doi.org/10.1016/j.fufo.2021.100058

Caniani, D., Caivano, M., Pascale, R., Bianco, G., Mancini, I.M., Masi, S., Mazzone, G., Firouzian, M., Rosso, D., 2019. CO_2 and N_2O from water resource recovery facilities: Evaluation of emissions from biological treatment, settling, disinfection, and receiving water body. Science of the Total Environment 648, 1130-1140. https://doi.org/10.1016/j.scitotenv.2018.08.150

Carvalho, J.L.N., Nogueirol, R.C., Menandro, L.M.S., Bordonal, R.d.O., Borges, C.D., Cantarella, H., Franco, H.C.J., 2017. Agronomic and environmental implications of sugarcane straw removal: a major review. GCB Bioenergy 9, 1181-1195. https://doi.org/10.1111/gcbb.12410

Chala, B., Oechsner, H., Latif, S., Müller, J., 2018. Biogas Potential of Coffee Processing Waste in Ethiopia. Sustainability 10, 2678. https://doi.org/10.3390/su10082678

Charteris, A.F., Chadwick, D.R., Thorman, R.E., Vallejo, A., de Klein, C.A.M., Rochette, P., Cárdenas, L.M., 2020. Global Research Alliance N_2O chamber methodology guidelines: Recommendations for deployment and accounting for sources of variability. Journal of Environmental Quality 49, 1092-1109. https://doi.org/10.1002/jeq2.20126

Chen, R., Wang, Y., Wang, W., Wei, S., Jing, Z., Lin, X., 2015. N_2O emissions and nitrogen transformation during windrow composting of dairy manure. Journal of Environmental Management 160, 121-127. https://doi.org/10.1016/j.jenvman.2015.06.021

Clough, T.J., Rochette, P., Thomas, S.M., Pihlatie, M., Christiansen, J.R., Thorman, R.E., 2020. Global Research Alliance N_2O chamber methodology guidelines: Design considerations. Journal of Environmental Quality 49, 1081-1091. https://doi.org/10.1002/jeq2.20117

Czepiel, P., Douglas, E., Harriss, R., Crill, P., 1996. Measurements of N_2O from composted organic wastes. Environmental Science & Technology 30, 2519-2525. https://doi.org/10.1021/es950841j

Dadi, D., Daba, G., Beyene, A., Luis, P., Van der Bruggen, B., 2019. Composting and co-composting of coffee husk and pulp with source-separated municipal solid waste: a breakthrough in valorization of coffee waste. International Journal of Recycling of Organic Waste in Agriculture 8, 263-277. https://doi.org/10.1007/s40093-019-0256-8

de Klein, C.A.M., Harvey, M.J., Clough, T.J., Petersen, S.O., Chadwick, D.R., Venterea, R.T., 2020. Global Research Alliance N2O chamber methodology guidelines: Introduction, with health and safety considerations. Journal of Environmental Quality 49, 1073-1080. https://doi.org/https://doi.org/10.1002/jeq2.20131

del Real Olvera, J., Lopez-Lopez, A., 2012. Biogas production from anaerobic treatment of agro-industrial wastewater, In: Kumar, S. (Ed.), Biogas. IntechOpen, Rijeka, Croatia.

DelSontro, T., Boutet, L., St-Pierre, A., del Giorgio, P.A., Prairie, Y.T., 2016. Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity. Limnology and Oceanography 61, S62-S77. https://doi.org/10.1002/lno.10335

Duchemin, E., Lucotte, M., Canuel, R., 1999. Comparison of static chamber and thin boundary layer equation methods for measuring greenhouse gas emissions from large water bodies. Environmental Science & Technology 33, 350-357. https://doi.org/10.1021/es9800840

Echeverria, M., Nuti, M., 2017. Valorisation of the residues of coffee agro-industry: perspectives and limitations. The Open Waste Management Journal 10. https://doi.org/10.2174/1876400201710010013

Enström, A., Haatainen, T., Suharto, A., Giebels, M., Lee, K.Y., 2019. Introducing a new GHG emission calculation approach for alternative methane reduction measures in the wastewater treatment of a palm oil mill. Environment, Development and Sustainability 21, 3065-3076. https://doi.org/10.1007/s10668-018-0181-4

Esteca, F.d.C.N., Rodrigues, L.R., de Moraes, G.J., Júnior, I.D., Klingen, I., 2018. Mulching with coffee husk and pulp in strawberry affects edaphic predatory mite and spider mite densities. Experimental and Applied Acarology 76, 161-183. https://doi.org/10.1007/s10493-018-0309-0

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D., Mauritsen, T., Palmer, M., Watanabe, M., et al., 2021. Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity, In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054.

Fukumoto, Y., Osada, T., Hanajima, D., Haga, K., 2003. Patterns and quantities of NH_3, N_2O and CH_4 emissions during swine manure composting without forced aeration––effect of compost pile scale. Bioresource Technology 89, 109-114. https://doi.org/10.1016/S0960-8524(03)00060-9

Gaia Cacao, B.V., 2021. Global Cocoa Market Study: Project coordinated by the International Executive Service Corps (IESC) with advice of the Fine Cacao and Chocolate Institute (FCCI) and funded by the U.S. Department of Agriculture (USDA), Amsterdam.

Genanaw, W., Kanno, G.G., Derese, D., Aregu, M.B., 2021. Effect of Wastewater Discharge From Coffee Processing Plant on River Water Quality, Sidama Region, South Ethiopia. Environmental Health Insights 15, 11786302211061047. https://doi.org/10.1177/11786302211061047

Grace, P.R., van der Weerden, T.J., Rowlings, D.W., Scheer, C., Brunk, C., Kiese, R., Butterbach-Bahl, K., Rees, R.M., Robertson, G.P., Skiba, U.M., 2020. Global Research Alliance N_2O chamber methodology guidelines: Considerations for automated flux measurement. Journal of Environmental Quality 49, 1126-1140. https://doi.org/10.1002/jeq2.20124

Hanc, A., Hrebeckova, T., Grasserova, A., Cajthaml, T., 2021. Conversion of spent coffee grounds into vermicompost. Bioresource Technology 341, 125925. https://doi.org/10.1016/j.biortech.2021.125925

Ho, L., Jerves-Cobo, R., Morales, O., Larriva, J., Arevalo-Durazno, M., Barthel, M., Six, J., Bode, S., Boeckx, P., Goethals, P., 2021. Spatial and temporal variations of greenhouse gas emissions from a waste stabilization pond: Effects of sludge distribution and accumulation. Water Research 193, 116858. https://doi.org/10.1016/j.watres.2021.116858

Hougni, D.G.J.M., Schut, A.G.T., Woittiez, L.S., Vanlauwe, B., Giller, K.E., 2021. How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching. Plant and Soil 463, 155-170. https://doi.org/10.1007/s11104-021-04885-1

Hrad, M., Binner, E., Piringer, M., Huber-Humer, M., 2014. Quantification of methane emissions from full-scale open windrow composting of biowaste using an inverse dispersion technique. Waste Management 34, 2445-2453. https://doi.org/10.1016/j.wasman.2014.08.013

Hüppi, R., Felber, R., Krauss, M., Six, J., Leifeld, J., Fuß, R., 2018. Restricting the nonlinearity parameter in soil greenhouse gas flux calculation for more reliable flux estimates. PLOS ONE 13, e0200876. https://doi.org/10.1371/journal.pone.0200876

ICCO, 2023. International Cocoa Organization: Quarterly Bulletin of Cocoa Statistics, Vol. XLIX, No. 4, Cocoa year 2022/23, Abidjan, Côte d'Ivoire.

ICO, 2011. Rules on statistics statistical reports, International coffee council. International coffee council, London, United Kingdom, p. 28.

ICO, December 2023. Coffee Report and Outlook (CRO). International Coffee Organization, London.

Ijanu, E.M., Kamaruddin, M.A., Norashiddin, F.A., 2019. Coffee processing wastewater treatment: a critical review on current treatment technologies with a proposed alternative. Applied Water Science 10, 11. https://doi.org/10.1007/s13201-019-1091-9

Iriondo-DeHond, A., Iriondo-DeHond, M., del Castillo, M.D., 2020. Applications of compounds from coffee processing by-products. Biomolecules 10, 1219

Jahangir, M.M.R., Johnston, P., Khalil, M.I., Grant, J., Somers, C., Richards, K.G., 2012. Evaluation of headspace equilibration methods for quantifying greenhouse gases in groundwater. Journal of Environmental Management 111, 208-212. https://doi.org/10.1016/j.jenvman.2012.06.033

Kent, E.R., Bailey, S.K., Stephens, J., Horwath, W.R., Paw U, K.T., 2019. Measurements of greenhouse gas flux from composting green-waste using micrometeorological mass balance and flow-through chambers. Compost Science & Utilization 27, 97-115. https://doi.org/10.1080/1065657X.2019.1571462

Krupa, S.V., 2003. Effects of atmospheric ammonia (NH_3) on terrestrial vegetation: a review. Environmental Pollution 124, 179-221. https://doi.org/10.1016/S0269-7491(02)00434-7

Kumar, A., Alaimo, C.P., Horowitz, R., Mitloehner, F.M., Kleeman, M.J., Green, P.G., 2011. Volatile organic compound emissions from green waste composting: Characterization and ozone formation. Atmospheric Environment 45, 1841-1848. https://doi.org/10.1016/j.atmosenv.2011.01.014

Kumar, A., Bhatia, A., Sehgal, V.K., Tomer, R., Jain, N., Pathak, H., 2021. Net ecosystem exchange of carbon dioxide in rice-spring wheat system of northwestern indo-gangetic plains. Land 10, 701. https://doi.org/10.3390/land10070701

Lambert, M., Fréchette, J.-L., 2005. Analytical techniques for measuring fluxes of CO_2 and CH_4 from hydroelectric reservoirs and natural water bodies, In: Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M. (Eds.), Greenhouse gas emissions — Fluxes and processes: hydroelectric reservoirs and natural environments. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 37-60.

Maier, M., Weber, T.K.D., Fiedler, J., Fuß, R., Glatzel, S., Huth, V., Jordan, S., Jurasinski, G., Kutzbach, L., Schäfer, K., et al., 2022. Introduction of a guideline for measurements of greenhouse gas fluxes from soils using non-steady-state chambers. Journal of Plant Nutrition and Soil Science 185, 447-461. https://doi.org/10.1002/jpln.202200199

Malyan, S.K., Singh, O., Kumar, A., Anand, G., Singh, R., Singh, S., Yu, Z., Kumar, J., Fagodiya, R.K., Kumar, A., 2022. Greenhouse gases trade-off from ponds: An overview of emission process and their driving factors. Water 14, 970. https://doi.org/10.3390/w14060970

Mariatti, F., Gunjević, V., Boffa, L., Cravotto, G., 2021. Process intensification technologies for the recovery of valuable compounds from cocoa by-products. Innovative Food Science & Emerging Technologies 68, 102601. https://doi.org/10.1016/j.ifset.2021.102601

Martínez, R., Torres, P., Meneses, M.A., Figueroa, J.G., Pérez-Álvarez, J.A., Viuda-Martos, M., 2012. Chemical, technological and in vitro antioxidant properties of cocoa (*Theobroma cacao L.*) co-products. Food Research International 49, 39-45. https://doi.org/10.1016/j.foodres.2012.08.005

Mendoza Martinez, C.L., Saari, J., Melo, Y., Cardoso, M., de Almeida, G.M., Vakkilainen, E., 2021. Evaluation of thermochemical routes for the valorization of solid coffee residues to produce biofuels: A Brazilian case. Renewable and Sustainable Energy Reviews 137, 110585. https://doi.org/10.1016/j.rser.2020.110585

Mønster, J.G., Samuelsson, J., Kjeldsen, P., Rella, C.W., Scheutz, C., 2014. Quantifying methane emission from fugitive sources by combining tracer release and downwind measurements – A sensitivity analysis based on multiple field surveys. Waste Management 34, 1416-1428. https://doi.org/10.1016/j.wasman.2014.03.025

Munongo, M.E., Nkeng, G.E., Njukeng, J.N., 2017. Production and characterization of compost manure and biochar from cocoa pod husks. International Journal of Advanced Scientific Research and Management 2, 26-31

Nicoloso, R.d.S., Bayer, C., Denega, G.L., Oliveira, P.A.V.d., Higarashi, M.M., Corrêa, J.C., Lopes, L.d.S., 2013. Gas chromatography and photoacoustic spectroscopy for the assessment of soil greenhouse gases emissions. Ciência Rural 43. https://doi.org/10.1590/S0103-84782013000200012

Nordahl, S.L., Devkota, J.P., Amirebrahimi, J., Smith, S.J., Breunig, H.M., Preble, C.V., Satchwell, A.J., Jin, L., Brown, N.J., Kirchstetter, T.W., et al., 2020. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. Environmental Science & Technology 54, 9200-9209. https://doi.org/10.1021/acs.est.0c00364

Nordahl, S.L., Preble, C.V., Kirchstetter, T.W., Scown, C.D., 2023. Greenhouse gas and air pollutant emissions from composting. Environmental Science & Technology 57, 2235-2247. https://doi.org/10.1021/acs.est.2c05846

Novita, E., 2016. Biodegradability Simulation of Coffee Wastewater Using Instant Coffee. Agriculture and Agricultural Science Procedia 9, 217-229. https://doi.org/10.1016/j.aaspro.2016.02.138

Oddoye, E.O.K., Agyente-Badu, C.K., Gyedu-Akoto, E., 2013. Cocoa and its by-products: Identification and utilization, In: Watson, R.R., Zibadi, S., Preedy, V.R. (Eds.), Chocolate in health and nutrition. Springer New York Heidelberg Dordrecht London, London, pp. 23-37.

Oliveira, B.G., Carvalho, J.L.N., Chagas, M.F., Cerri, C.E.P., Cerri, C.C., Feigl, B.J., 2017. Methane emissions from sugarcane vinasse storage and transportation systems: Comparison between open channels and tanks. Atmospheric Environment 159, 135-146. https://doi.org/10.1016/j.atmosenv.2017.04.005

Oliveira, B.G.d., Nunes Carvalho, J.L., Pellegrino Cerri, C.E., Cerri, C.C., Feigl, B.J., 2015. Greenhouse gas emissions from sugarcane vinasse transportation by open channel: a case study in Brazil. Journal of Cleaner Production 94, 102-107. https://doi.org/10.1016/j.jclepro.2015.02.025

Oliveira, L.S., Franca, A.S., 2015. Chapter 31 - An Overview of the Potential Uses for Coffee Husks, In: Preedy, V.R. (Ed.), Coffee in Health and Disease Prevention. Academic Press, San Diego, pp. 283-291.

Oller, I., Malato, S., Sánchez-Pérez, J.A., 2011. Combination of Advanced Oxidation Processes and biological treatments for wastewater decontamination—A review. Science of the Total Environment 409, 4141-4166. https://doi.org/10.1016/j.scitotenv.2010.08.061

Pan, Y., van den Akker, B., Ye, L., Ni, B.-J., Watts, S., Reid, K., Yuan, Z., 2016. Unravelling the spatial variation of nitrous oxide emissions from a step-feed plug-flow full scale wastewater treatment plant. Scientific Reports 6, 20792. https://doi.org/10.1038/srep20792

Park, J.B., Craggs, R.J., 2007. Biogas production from anaerobic waste stabilisation ponds treating dairy and piggery wastewater in New Zealand. Water Sci Technol 55, 257-264. https://doi.org/10.2166/wst.2007.357

Pin, B.V.d.R., Barros, R.M., Silva Lora, E.E., Almazan del Olmo, O., Silva dos Santos, I.F., Ribeiro, E.M., Victor de Freitas Rocha, J., 2020. Energetic use of biogas from the anaerobic digestion of coffee wastewater in southern Minas Gerais, Brazil. Renewable Energy 146, 2084-2094. https://doi.org/10.1016/j.renene.2019.08.004

Pinzon-Nuñez, D.A., Adarme-Duran, C.A., Vargas-Fiallo, L.Y., Rodriguez-Lopez, N., Rios-Reyes, C.A., 2022. Biochar as a waste management strategy for cadmium contaminated cocoa pod husk residues. International journal of recycling organic waste in agriculture 11, 101-115. https://doi.org/10.30486/ijrowa.2021.1920124.1192

Pires, J.F., Schwan, R.F., Silva, C.F., 2019. Assessing the efficiency in assisted depuration of coffee processing wastewater from mixed wild microbial selected inoculum. Environmental Monitoring and Assessment 191, 284. https://doi.org/10.1007/s10661-019-7398-z

Porto de Souza Vandenberghe, L., Kley Valladares-Diestra, K., Amaro Bittencourt, G., Fátima Murawski de Mello, A., Sarmiento Vásquez, Z., Zwiercheczewski de Oliveira, P., Vinícius de Melo Pereira, G., Ricardo Soccol, C., 2022. Added-value biomolecules' production from cocoa pod husks: A review. Bioresource Technology 344, 126252. https://doi.org/10.1016/j.biortech.2021.126252

Preble, C.V., Chen, S.S., Hotchi, T., Sohn, M.D., Maddalena, R.L., Russell, M.L., Brown, N.J., Scown, C.D., Kirchstetter, T.W., 2020. Air pollutant emission rates for dry anaerobic digestion and composting of organic municipal solid waste. Environmental Science & Technology 54, 16097-16107. https://doi.org/10.1021/acs.est.0c03953

Pulleman, M.M., Rahn, E., Valle, J.F., 2023. Regenerative agriculture for low-carbon and resilient coffee farms: A practical guidebook. International Center for Tropical Agriculture (CIAT), Cali (Colombia), p. 181.

Raphael, K., Sureka, Velmourougane, K., 2012. Vermicomposting of Coffee Processing Wastes Using Exotic (Eudrilus Eugeniae) and Native Earthworm (Perionyx Ceylanesis) Species. Macromolecular Symposia 320, 61-69. https://doi.org/10.1002/masy.201251008

Rattan, S., Parande, A.K., Nagaraju, V.D., Ghiwari, G.K., 2015. A comprehensive review on utilization of wastewater from coffee processing. Environmental Science and Pollution Research 22, 6461-6472. https://doi.org/10.1007/s11356-015-4079-5

Ravishankara, A.R., Daniel, J.S., Portmann, R.W., 2009. Nitrous Oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. Science 326, 123-125. https://doi.org/10.1126/science.1176985

Rochette, P., Eriksen-Hamel, N.S., 2008. Chamber measurements of soil nitrous oxide flux: Are absolute values reliable? Soil Science Society of America Journal 72, 331-342. https://doi.org/10.2136/sssaj2007.0215

Said, N.S.M., Abdullah, S.R.S., Ismail, N.I., Hasan, H.A., Othman, A.R., 2023. Integrating treatment processes of coffee processing mill effluent for reclamation of secondary resources. Journal of Cleaner Production 386, 135837. https://doi.org/10.1016/j.jclepro.2022.135837

San Martin Ruiz, M., Reiser, M., Hafner, G., Kranert, M., 2018. A Study about methane emissions from different composting systems for coffee by-products on Costa Rica. Environment and Ecology Research. https://doi.org/10.13189/eer.2018.060506

San Martin Ruiz, M., Reiser, M., Kranert, M., 2020. Enhanced composting as a way to a climate-friendly management of coffee by-products. Environ Sci Pollut Res Int 27, 24312-24319. https://doi.org/10.1007/s11356-020-08742-z

San Martin Ruiz, M., Reiser, M., Kranert, M., 2021. Composting and methane emissions of coffee by-products. Atmosphere 12, 1153. https://doi.org/10.3390/atmos12091153

Sánchez, M., Laca, A., Laca, A., Díaz, M., 2023. Cocoa Bean Shell: A By-Product with High Potential for Nutritional and Biotechnological Applications. Antioxidants (Basel) 12. https://doi.org/10.3390/antiox12051028

Scheutz, C., Samuelsson, J., Fredenslund, A.M., Kjeldsen, P., 2011. Quantification of multiple methane emission sources at landfills using a double tracer technique. Waste Management 31, 1009-1017. https://doi.org/10.1016/j.wasman.2011.01.015

Sengupta, B., Priyadarshinee, R., Roy, A., Banerjee, A., Malaviya, A., Singha, S., Mandal, T., Kumar, A., 2020. Toward sustainable and eco-friendly production of coffee: abatement of wastewater and evaluation of its potential valorization. Clean Technologies and Environmental Policy 22, 995-1014. https://doi.org/10.1007/s10098-020-01841-y

Serna-Jiménez, J.A., Siles, J.A., de los Ángeles Martín, M., Chica, A.F., 2022. A Review on the Applications of Coffee Waste Derived from Primary Processing: Strategies for Revalorization. Processes 10, 2436

Silva, J.P., Lasso, A., Lubberding, H.J., Peña, M.R., Gijzen, H.J., 2015. Biases in greenhouse gases static chambers measurements in stabilization ponds: Comparison of flux estimation using linear and non-linear models. Atmospheric Environment 109, 130-138. https://doi.org/10.1016/j.atmosenv.2015.02.068

Sommer, S.G., McGinn, S.M., Hao, X., Larney, F.J., 2004. Techniques for measuring gas emissions from a composting stockpile of cattle manure. Atmospheric Environment 38, 4643-4652. https://doi.org/10.1016/j.atmosenv.2004.05.014

Tekle, D.Y., Hailu, A.B., Wassie, T.A., Tesema, A.G., 2015. Effect of coffee processing plant effluent on the physicochemical properties of receiving water bodies, Jimma zone Ethiopia. American Journal of Environmental Protection 4, 83-90. https://doi.org/10.11648/j.ajep.20150402.12

Valadez-Carmona, L., Ortiz-Moreno, A., Ceballos-Reyes, G., Mendiola, J.A., Ibáñez, E., 2018. Valorization of cacao pod husk through supercritical fluid extraction of phenolic compounds. The Journal of Supercritical Fluids 131, 99-105. https://doi.org/10.1016/j.supflu.2017.09.011

Vásquez, Z.S., de Carvalho Neto, D.P., Pereira, G.V.M., Vandenberghe, L.P.S., de Oliveira, P.Z., Tiburcio, P.B., Rogez, H.L.G., Góes Neto, A., Soccol, C.R., 2019. Biotechnological approaches for cocoa waste management: A review. Waste Management 90, 72-83. https://doi.org/10.1016/j.wasman.2019.04.030

Walter, K.M., Chanton, J.P., Chapin III, F.S., Schuur, E.A.G., Zimov, S.A., 2008. Methane production and bubble emissions from arctic lakes: Isotopic implications for source pathways and ages. Journal of Geophysical Research: Biogeosciences 113. https://doi.org/10.1029/2007JG000569

Wood, J.D., VanderZaag, A.C., Wagner-Riddle, C., Smith, E.L., Gordon, R.J., 2014. Gas emissions from liquid dairy manure: complete versus partial storage emptying. Nutrient Cycling in Agroecosystems 99, 95-105. https://doi.org/10.1007/s10705-014-9620-2

Yang, P., Tang, K.W., Yang, H., Tong, C., Zhang, L., Lai, D.Y.F., Hong, Y., Tan, L., Zhu, W., Tang, C., 2023. Contrasting effects of aeration on methane (CH_4) and nitrous oxide (N_2O) emissions from subtropical aquaculture ponds and implications for global warming mitigation. Journal of Hydrology 617, 128876. https://doi.org/10.1016/j.jhydrol.2022.128876

Ye, L., Ni, B.-J., Law, Y., Byers, C., Yuan, Z., 2014. A novel methodology to quantify nitrous oxide emissions from full-scale wastewater treatment systems with surface aerators. Water Research 48, 257-268. https://doi.org/10.1016/j.watres.2013.09.037

Zhao, J., Zhang, M., Xiao, W., Jia, L., Zhang, X., Wang, J., Zhang, Z., Xie, Y., Pu, Y., Liu, S., et al., 2021. Large methane emission from freshwater aquaculture ponds revealed by long-term eddy covariance observation. Agricultural and Forest Meteorology 308-309, 108600. https://doi.org/10.1016/j.agrformet.2021.108600

Zhu-Barker, X., Bailey, S.K., Paw U, K.T., Burger, M., Horwath, W.R., 2017. Greenhouse gas emissions from green waste composting windrow. Waste Management 59, 70-79. https://doi.org/10.1016/j.wasman.2016.10.004

Glossary

BOD: The biochemical oxygen demand represents the amount of dissolved oxygen consumed by biological organisms when they decompose organic matter in water.

Carbon footprint of a product: A carbon footprint is the total amount of greenhouse gases (including CO_2, CH_4, and N_2O) that are generated by a specific activity, such as coffee and cocoa production. At ISO 14067:2018 the Carbon footprint is defined as a sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change.

CH_4: Methane is a hydrocarbon that is a primary component of natural gas. CH_4 is also a GHG, so its presence in the atmosphere affects the earth's temperature and climate system.

Cherry: A small, soft round stone fruit that is typically bright or dark red. The coffee fruit is called coffee cherry.

Climate change: It is the significant variation of average weather conditions becoming, for example, warmer, wetter, or drier—over several decades or longer.

CO_2 equivalent: Unit for comparing the radiative forcing of Greenhouse gases to that of carbon dioxide (CO_2) (ISO 14067:2018 definition). The mass of CO_2 (expressed in kilograms or tons) needed to produce the same global warming effect as another greenhouse gas. Since gases vary in their radiative efficiency and lifetime in the atmosphere, they also vary in terms of global warming potential. This expresses how much energy the emissions of 1 ton of a gas will absorb over a given period (generally 100 years) relative to the emission of 1 ton of CO_2, providing a common unit of measurement for adding up emission estimates of the three different gases to calculate the total carbon footprint of a farm or product. IPCC definition.

Cocoa Pod Husk (CPH): Residue by-product of cocoa production, obtained after the removal of the cocoa beans from the fruit.

Coffea arabica: The most commonly produced species of coffee in the world, also known as Arabica coffee.

Coffea canephora: It is a species of coffee that originated in central and western sub-Saharan Africa. Beans tend to have lower acidity, more bitterness, and a more woody and less fruity flavor compared to *Coffea arabica* beans. Usually is called Coffea robusta, or commonly robusta coffee

Coffee husk: The dry outer covering of coffee fruits or seeds, comprise dry pulp and parchment (skin/peel, pulp, mucilage and parchment).

COD: The chemical oxygen demand is the amount of oxygen consumed when the water sample is chemically oxidised.

Compost: A carbon-rich soil amendment produced by microbial decomposition of organic residues or waste, which has reached a level of maturity or stability that allows to supply nutrients to plants and improve soil health.

Composting: Aerobic process designed to produce compost (ISO 18606:2013 definition).

Ecological footprint: The impact of a person or community on the environment, expressed as the amount of land required to sustain their use of natural resources.

GHG: Gaseous constituent of the atmosphere, both natural and anthropogenic (such as CO_2, CH_4, and N_2O), that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth’s surface, the atmosphere and clouds (trap heat) (ISO 14067:2018 definition).

Global warming potential: A means of comparing the impacts of different GHGs based on two factors: their "radiative efficiency" (or ability to absorb energy) and their “lifetime” (i.e., the amount of time they remain in the atmosphere). The global warming potential of a GHG is used to calculate CO_2 equivalents.

High-strength wastewater: wastewater having a 30-day average concentration of BOD greater than 300 mg L^{-1} or of total suspended solids (TSS) greater than 330 mg L^{-1}.

Mucilage: It is the inner layer of the pulp. There's also a layer of pectin underneath the mucilage. These layers are full of sugars, which are important during the fermentation process.

N_2O: Under normal environmental conditions dinitrogen oxide (more commonly known as nitrous oxide) is a colourless gas. Nitrous oxide, also known as “laughing gas,” is the most important GHG after CH_4 and CO_2 related to global warming, and the biggest human-related threat to the ozone layer.

Parchment: Layer that protects the coffee bean and resembles parchment paper when dried.

Peel: The outer covering of the coffee fruit (coffee cherry).

Ponds: A small body of still water and wastewater formed by artificial means.

Pulp: it is the stringy content of the fruit's endocarp. The pulp contains the juice of the fruit.

Residue (also “Waste”): Substances or objects that the holder intends or is required to dispose of (ISO 14067:2018 definition).

Robusta: It is the plant of the species *Coffea canephora,* especially *C. canephora var. robusta*.

Sweating: It is a cloudy liquid known produced during the fermentation of the cocoa mucilage.

VOC: Volatile organic compounds are organic compounds that have a high vapour pressure at room temperature, such as isoprene, terpenes and methanol.

Annexes

Annex 1. Advantages and disadvantages of the gas sampling methods used to measure emissions in compost factories and water bodies, as found in the literature. These methods are not appropriate for sampling gases from compost heaps and wastewater ponds.

MEASUREMENT APPROACH	ADVANTAGES	DISADVANTAGES
Compost		
Gas Probes	1. Provide a more comprehensive analysis beyond surface emissions 2. Determines gas concentrations at different depths within the windrow. 3. This method provides insights into composting dynamics, such as regions with anaerobic activity and elevated CH_4 concentrations. 4. Easy method, which can be used in a wide range of experiments. 5. Suitable for laboratory experiments.	1. The gas probes measure gas concentration (potential emissions), not necessarily direct releases into the atmosphere. Concentrations are indicator for risk of emission 2. Modeling surface emissions is based on a lot of assumptions and is particularly difficult for N_2O and CH_4 as both undergo production and consumption in the profile 3. Small surface area compared to the entire composting pile (windrow). *Not a disadvantage itself:* 4. For manual sampling (not applicable to automatic machines) the measurement of gases is not conducted continuously; it is done intermittently over a specified period and area. It is possible to use data loggers. 5. For manual sampling (not applicable to automatic machines) needs to follow the event-based sampling approach. Based on this, high peaks can be missed due to the lack of sampling. 6. For manual sampling (not applicable to automatic machines) it is a time-consuming technique.
Tracer Releases	1. Is useful for large-scale studies. 2. By tracking its dispersion and concentration downwind, researchers estimate emission rates of other gases, including GHGs.	1. It is not a direct method. 2. Require the controlled release of a tracer gas. 3. Assume that the released tracer will disperse in the atmosphere in the same way as CH_4 emitted from the open windrows. 4. While useful for large-scale studies, it may not be necessary for smaller composting operations. 5. Does not enable the differentiation of emissions across the pile's surface area. 6. The method needs to be pre-tested using a synthetic area source with known CH_4/N_2O and the trace gas at different meteorological conditions. 7. Requires expensive instrumentation, such as a sonic anemometer and high-precision, high-frequency gas analysers.
Inverse Dispersion Analysis	1. Is useful for large-scale studies, such as landfills agricultural operations. 2. Emission rates could be quantified with an uncertainty of less than 10–20%.	1. It relies on complex mathematical models to estimate emissions. 2. Does not enable the differentiation of emissions across the pile's surface area. 3. Needs to be combined with meteorological data. 4. Different parameters are needed, at least 4: wind direction, wind speed or friction velocity, the Obukhov length L and surface roughness length. 5. The technique depends on a good description of atmospheric transport, which is known to be difficult in extreme stability conditions.

		6. While it's valuable for some emissions studies, its relevance to coffee and cocoa compost production may be limited due to the specific nature and scale of these operations. 7. The method needs to be pre-tested using a synthetic area source with known CH_4/N_2O and the trace gas at different meteorological conditions and laser path arrangements in an ideal surface-layer setting.
Micrometeorological Mass Balance	1. Is useful mainly for large-scale studies. 2. It is a total-emission method, providing a good estimate of emissions from full-scale composting plants. 3. It is often used for larger agricultural operations or industrial sites 4. It is are non-intrusive, 5. Can provide increased temporal sampling frequency, and may be used to check and/or improve flux estimates obtained from chamber measurements.	1. In smaller-scale coffee and cocoa composting operations, simpler methods are better for GHG quantification. 2. Does not enable the differentiation of emissions across the pile's surface area. 3. Needs to be combined with meteorological data, such as wind speed. 4. Needs emission and wind data at multiple points within an area. 5. Does not enable the differentiation of emissions across the pile's surface area. 6. Assumes a homogeneous emitting area. 7. The main disadvantage of these methods the requirement for additional equipment to measure gas concentration and wind speed profiles in the field, necessitating at least two separate locations.
Dynamic plume tracer dispersion	1. Is useful mainly for large-scale studies. 2. It is a total-emission method, providing a good estimate of emissions from full-scale composting plants. 3. An alternative method for quantification of whole emissions, which when combined with meteorological data and atmospheric dispersion modelling can provide an integrated measure of whole compost pile fluxes.	1. It is not a direct method. 2. Is not useful for small-scale studies, such as emissions from compost piles. 3. Require the controlled release of a tracer gas. Such as Sulphur hexafluoride (SF_6), N_2O or acetylene (C_2H_2), which itself has a high global warming potential. 4. It is a double tracer technique that combines controlled tracer gas release from the compost pile with time-resolved concentration measurements downwind of the gas of interest. 5. Does not enable the differentiation of emissions across the pile's surface area. 6. It is a time and labour-consuming technique.
Wastewater ponds, water bodies, and lakes		
Eddy co-variance	1. Is useful mainly for large-scale studies. 2. It is a total-emission method, providing a good estimate of emissions from full-scale pond plants 3. It is often used for larger agricultural operations or industrial sites 4. It is non-intrusive 5. Can provide increased temporal sampling frequency, and may be used to check and/or improve flux estimates obtained from chamber measurements	**1.** This method is complex, expensive, and challenging to implement across multiple sites and fields simultaneously **2.** In smaller-scale coffee wastewater operations, simpler methods are better for GHG quantification **3.** Determining spatial variations on a very small scale is not feasible using towers **4.** Needs to be combined with meteorological data, such as wind speed **5.** It relies on complex mathematical models to estimate emissions