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Atmospheric emissions from emerging technologies used in cocoa bean drying processes

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Abstract

Atmospheric emissions from emerging technologies used in cocoa bean drying, along with their associated environmental impacts, are evaluated. A bibliographic review was conducted using the Web of Science, and a bibliometric analysis was performed with VOSviewer. Five emerging technologies used in cocoa post-harvest processing were identified: Samoa-type, tunnel or greenhouse-type, rotary or drum dryers, vertical or mixed-flow systems, and hybrid systems. Differences were observed in both the type and magnitude of emissions, with the main pollutants being CO, CO_2, NO_x, SO_2, PM, CH_4, and N_2O. Dryers using firewood as a biomass fuel release more air pollutants than hybrid or solar systems. The most significant environmental impacts are associated with emissions generated throughout the analyzed production chain. It is concluded that the identification of atmospheric emissions within the transition toward cleaner systems is essential to mitigating environmental effects in the cocoa sector.

Keywords: Atmospheric pollution, Crops, Drying, Environmental impact assessment, Technology.

1. Introduction

Cocoa (*Theobroma cacao L.*) is a crop of strategic relevance for several tropical economies, particularly in developing countries such as Colombia [1], where it constitutes an important source of income for rural communities and smallholder farmers. The post-harvest process, which includes fermentation and drying, plays a decisive role in the final quality of the beans and directly affects their flavor, aroma, and value in national and international markets [2], [3]. Drying is considered one of the most critical stages, not only due to its influence on organoleptic characteristics but also because of the environmental impacts it entails, particularly regarding atmospheric emissions generated during its operation [4], [5].

Traditionally, cocoa drying has been carried out naturally through solar radiation on patios or raised beds [6]. [7] However, variable climatic conditions [8]–[10], increasing global demand, and the need to improve process efficiency have driven the adoption of emerging drying technologies, including Samoa-type dryers, tunnel or greenhouse-type systems, rotary or drum dryers, vertical or mixed-flow dryers, and hybrid systems that combine conventional thermal sources with solar energy [10]. Nevertheless, the introduction of these technologies has brought new environmental challenges, among which the emission of atmospheric pollutants stands out [11].

The release of gaseous and particulate pollutants during grain drying, particularly when fossil fuels or biomass are used as thermal energy sources, includes carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), methane (CH_4), and nitrous oxide (N_2O), among others [12], [13]. These compounds pose risks to human health and the local environment, and contribute significantly to global climate change due to their atmospheric warming potential [7], [14].

Despite the importance of this topic, the scientific literature still presents gaps regarding comparative studies that integrate the analysis of cocoa drying technologies and their associated emissions and environmental impacts [15]. In this context, a systematic evaluation of the different available technological alternatives is required, considering both their energy efficiency and environmental footprint. Therefore, this study analyzes atmospheric emissions generated by emerging technologies used in cocoa bean drying through a bibliographic review of specialized databases such as *Web of Science*, and a bibliometric analysis using the VOSviewer tool [16]. The most common technologies, their associated pollutants, and related environmental impacts were examined.

2. Research method

An exploratory study with a quantitative approach was conducted, based on bibliographic analysis and structured into two phases:

2.1. Phase 1. Bibliographic review and selection

A systematic search was conducted in *Web of Science* for publications between 2019 and 2025. Open-access articles and documents were selected using keywords related to cocoa drying, emissions, and emerging technologies (Table 1). The first search equation yielded a total of 4,624 documents, from which 861 relevant articles were selected. The second search equation resulted in 1496 documents, of which 219 articles were selected. The selected documents were analyzed using the VOSviewer software in order to construct and visualize bibliometric networks.

Table 1. List of keywords and search equations used

No.	Keywords	Search equation	Documents retrieved
1	Emerging; Cocoa; Drying; Technologies	Emerging AND cocoa AND drying AND technologies	861
2	Air; Pollutants; Drying; Cocoa	Air pollutants AND drying cocoa	219

Figure 1 and Figure 2 present the main authors identified through the search equations ”Emerging AND cocoa AND drying AND technologies” and “Air pollutants AND drying cocoa,” respectively.

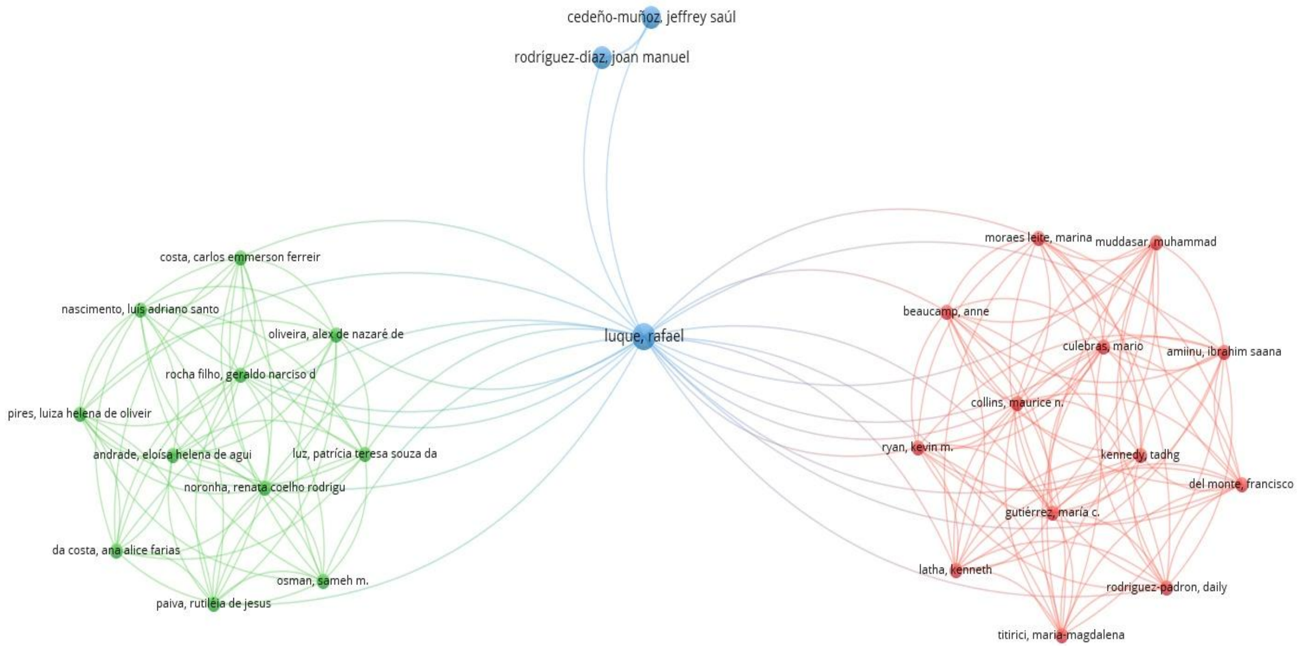

Figure 1. Main authors identified from the search equation “Emerging AND cocoa AND drying AND technologies”.

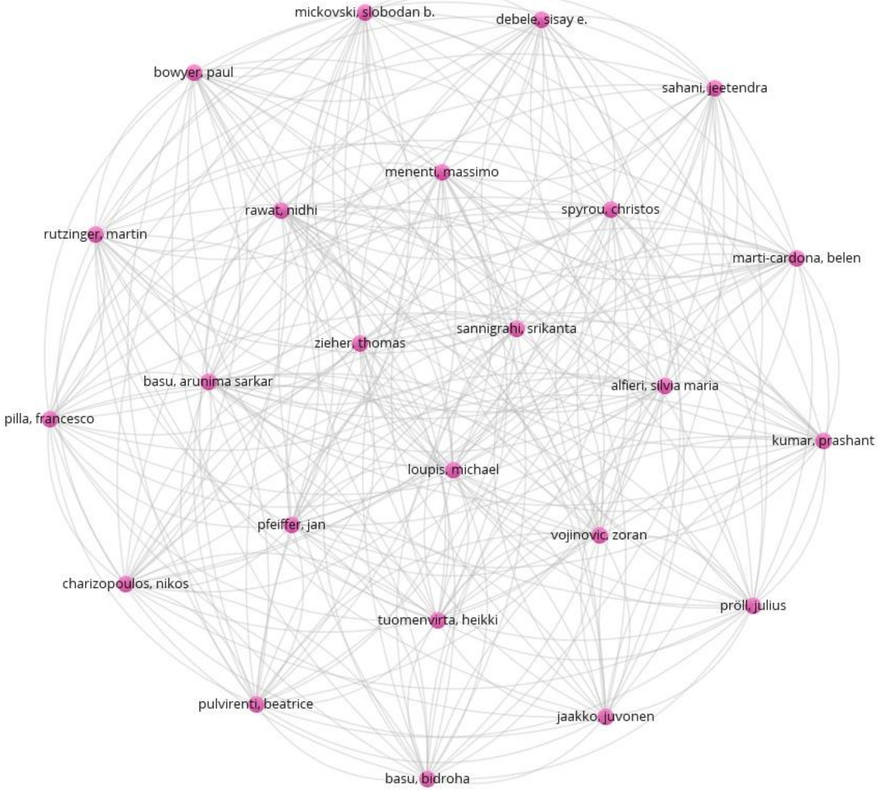

Figure 2. Top authors identified from the search query “Air pollutants AND drying cocoa”

2.2. Phase 2. Technical analysis

Based on the information collected during the bibliographic review and selection phase, a comparative matrix was developed, in which the emerging cocoa drying technologies most frequently reported by the authors were listed as a function of the main atmospheric pollutants (particularly those derived from biomass use) generated by each technology. This matrix served as the basis for identifying the environmental impacts associated with the defined atmospheric pollutants through the use of a process diagram and a matrix-based method.

3. Results and discussion

3.1. Description of emerging technologies used in the cocoa drying process

The bibliographic review enabled the identification of five technological alternatives applied to cocoa bean drying, based on their advantages and disadvantages (Table 2), from which the atmospheric pollutants associated with each were determined. It was found that each technology presents specific characteristics in terms of design, energy source, processing capacity, and level of control over the drying process, which influences aspects such as efficiency, the time required to achieve appropriate moisture levels, and the resources needed for implementation and maintenance.

Table 2. Overview of dryers used as emerging technologies for cocoa bean drying

Item	Dryers	Description	Advantages	Disadvantages
1	Samoa type dryers	A forced convection system that uses a wood- or biomass-fired furnace connected to a closed drying chamber with trays or grates for the beans [17].	- The indirect design prevents smoke contact with the product and enables gradual moisture evaporation. - Construction uses low-cost local materials such as metal and wood, and operates independently of climatic conditions, significantly accelerating drying compared to passive solar methods, reaching temperatures of 60–70 °C within a few hours, with thermal efficiencies of approximately 73–93% for 25 kg batches. - High drying rate, precise temperature control, and energy autonomy ensure more uniform and reliable production, particularly under adverse weather conditions.	- Proper system design and efficient ventilation are essential for optimal performance. - Uneven heat distribution or insufficient ventilation may reduce drying uniformity and increase fuel consumption. - Biomass selection must follow sustainability criteria.
2	Tunnel or greenhouse dryers	Enclosed structures made of transparent plastic materials that utilize solar energy to heat air, which circulates over cocoa beans arranged on trays or mesh beds,	- Air circulation can be natural or forced depending on system design. - Can operate naturally under high solar radiation conditions.	- Strong dependence on climatic conditions, which may affect process continuity during cloudy or rainy days unless hybrid

Item	Dryers	Description	Advantages	Disadvantages
		promoting dehydration [7], [18].	- Efficient use of solar energy. - Reduces dependence on non-renewable sources and lowers operating costs. - Minimizes contamination risks and improves drying uniformity and bean quality.	systems are integrated. - Requires significant initial investment and large land area.
3	Rotary or drum dryers	An inclined rotating cylinder where wet beans are repeatedly lifted and dropped while hot air flows through the drum. Two types exist: (a) direct heating, where combustion gases contact the beans; (b) indirect heating, where heat is transferred through the drum walls, avoiding direct contact [18].	- Enhances moisture evaporation and ensures uniform drying. - High processing capacity allows large volumes to be dried efficiently, regardless of climatic conditions. - Suitable for rainy seasons. - Precise control of temperature and residence time. - Improves final product quality.	- High energy consumption due to the use of heat sources, typically fossil fuels. - Higher operational costs and atmospheric pollutant emissions.
4	Vertical or mixed-flow dryers	Drying systems designed to dehydrate cocoa beans through controlled application of hot air, combining vertical and horizontal airflow for uniform heat distribution and efficient moisture removal [18].	- Vertical design enables downward grain movement by gravity, while forced hot air ensures homogeneous and continuous drying. - High efficiency significantly reduces drying time. - Independence from climatic conditions ensures consistent production and preserves bean quality. Suitable for humid regions and rainy seasons.	- High initial investment cost. - Significant energy consumption. - High operating costs. - Requires specialized maintenance. - Needs trained personnel for operation.
5	Hybrid drying systems	A technique that combines natural methods, such as	- Solar energy is used during the day to heat the air	- Under unfavorable weather conditions or at night,

Item	Dryers	Description	Advantages	Disadvantages
		solar energy, with artificial sources such as gas or electric heaters to optimize drying efficiency and reduce environmental impact [19], [20].	circulating in the drying chamber. - Maintains stable and optimal temperatures. - Improves bean quality and reduces drying time. - The integration of renewable energy sources reduces fuel consumption and atmospheric pollutant emissions. - Provides greater flexibility in the drying process. - Can adapt to changing climatic conditions. - Reduces operating costs.	conventional energy sources are required. - High initial investment cost. - System complexity may require specialized training and large installation areas.

3.2. Atmospheric pollutants generated by emerging technologies

Cocoa bean drying is a key stage in the production chain, as it reduces moisture content to optimal levels for storage, transportation, and commercialization [19]. The use of specific energy sources and materials in drying technologies may generate negative environmental impacts, particularly on the atmosphere [14]. In this context, these impacts are mainly associated with the release of compounds resulting from the use of solid, liquid, or gaseous fuels, as well as with the efficiency of combustion systems and the operating conditions during the process. Table 3 presents the main atmospheric pollutants generated during the operation of each of the reviewed emerging technologies, considering the technology used, the type of fuel, and the stage of the process.

Table 3. Comparative matrix of emerging cocoa drying technologies as a function of atmospheric emissions

Technologies	Energy source / Fuel	Process stage	Atmospheric pollutants
Samoa type dryers	Biomass (firewood)	Combustion chamber	Carbon monoxide (CO)
			Carbon dioxide (CO_2)
			Nitrogen oxides (NO_x)
			Particulate matter (PM)
			Polycyclic aromatic hydrocarbons (PAHs)
			Volatile organic compounds (VOCs)
			Soot and visible smoke
		Drying chamber	Polycyclic aromatic hydrocarbons (PAHs)
			Soot and visible smoke
Tunnel or greenhouse type dryers	Solar energy	Grain drying	Carbon dioxide (CO_2)
			Volatile organic compounds (VOCs)

Technologies	Energy source / Fuel	Process stage	Atmospheric pollutants
Rotary or drum dryers	Fossil fuels	Gas combustion	Carbon dioxide (CO_2)
			Nitrogen oxides (NO_x)
			Particulate matter (PM)
		Rotary drying process	Greenhouse gases (GHGs) - Methane (CH_4) - Nitrous oxide (N_2O)
Vertical or mixed flow dryers	Airflow / thermal energy	Burner chamber	Carbon dioxide (CO_2)
			Carbon monoxide (CO)
		Drying temperature conditions	Nitrogen oxides (NO_x)
		Combustion	Sulfur dioxide (SO_2)
		Dryer operation	Particulate matter (PM)
Hybrid dryers (natural and artificial methods)	Energy (solar + conventional)	Artificial method	Carbon dioxide (CO_2)
			Nitrogen oxides (NO_x)
			Carbon monoxide (CO)
			Particulate matter (PM)
			Greenhouse gases (GHGs) - Methane (CH_4) - Nitrous oxide (N_2O)
		Natural method	Particulate matter (PM)
			Carbon dioxide (CO_2)

The most common pollutants identified were carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), soot or visible smoke, and greenhouse gases [19], [14], such as methane (CH_4) and nitrous oxide (N_2O). Samoa-type dryers, which use firewood, generate the highest local emissions due to incomplete combustion, whereas tunnel or greenhouse dryers, based on solar energy, do not produce combustion pollutants, being limited to minimal VOC and dust emissions [7], [19].

In rotary dryers using fossil fuels, CO_2, NO_x, and particulate matter predominate, with potential contributions of CH_4 and N_2O. Vertical or mixed-flow dryers exhibit similar pollutants, with a higher risk of particle entrainment. Hybrid systems show a variable profile: clean during solar operation and producing fuel-related emissions during artificial heating. Therefore, solar-based technologies are the most environmentally favorable [21], while biomass and fossil fuel-based systems imply higher impacts. Proper technology selection, together with efficient combustion control and the implementation of mitigation measures, is crucial to reduce emissions and protect both air quality and product safety [22]–[25].

3.3. Identification of environmental impacts generated by emerging technologies

To identify the environmental impacts, a process diagram is presented (Figure 3), illustrating the sequence from the selection of the drying technology to the pollutants produced, which in turn lead to specific environmental impacts [24], [25]. This representation facilitates the analysis and understanding of the ecological consequences associated with these technologies [26]–[30].

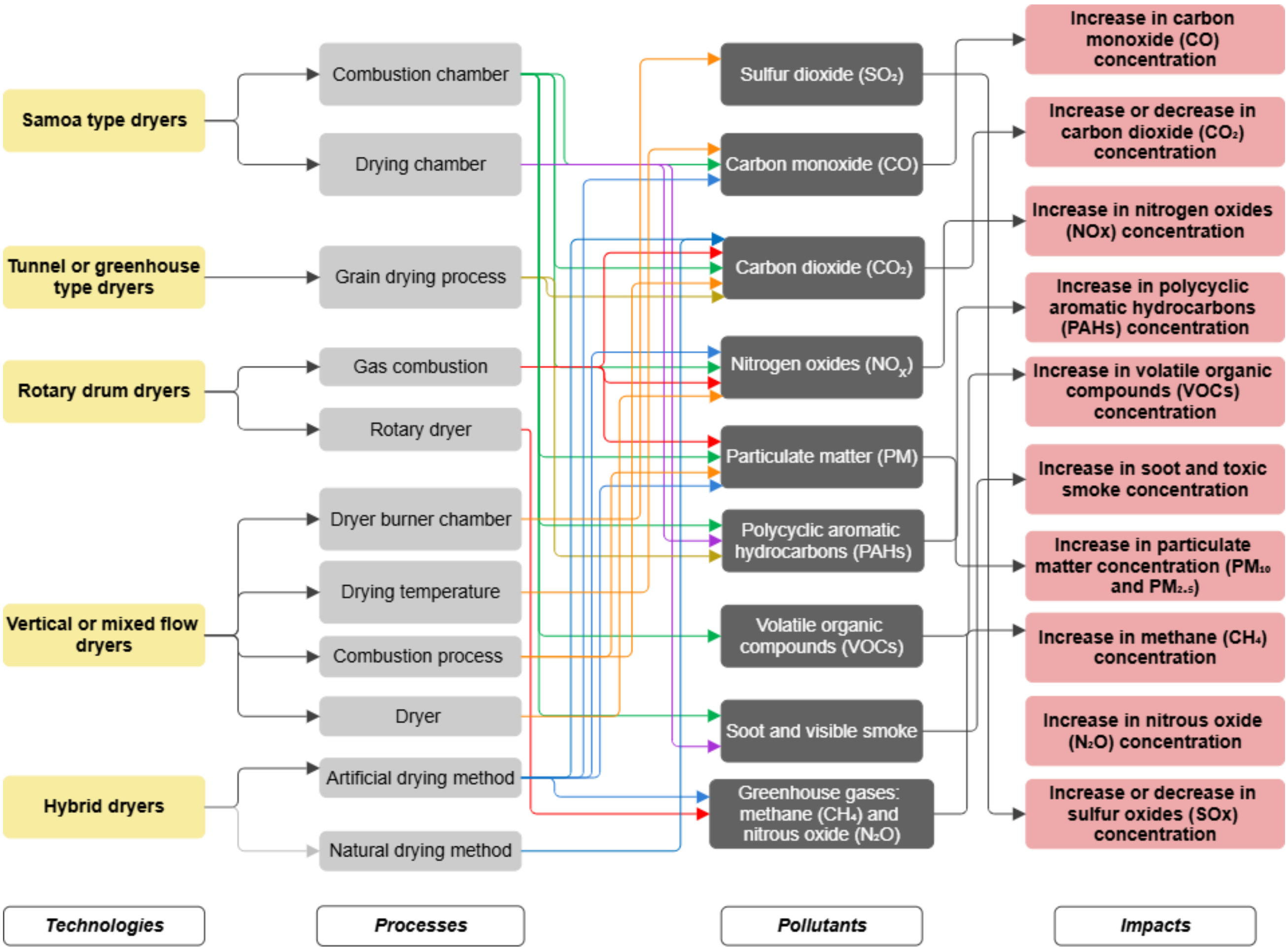

Figure 3. Process diagram showing the relationship between technologies, pollutants, and environmental impacts

In total, ten direct impacts were identified (Figure 3), from which indirect impacts were quantified using the matrix method as an analytical tool (Table 4). Samoa-type and hybrid drying technologies recorded the highest number of environmental effects, with 18 and 16 impacts, respectively, reflecting a high pollutant load and a significant interaction of multiple contaminants with both direct and indirect effects on the environment and public health [28], [29]. The diversity of emitted pollutants, including greenhouse gases, particulate matter, VOCs, NO_x, SO_x, and toxic compounds, further increases their potential to affect air quality and contribute to climate change, as reported by [10] and [20].

In contrast, vertical or mixed-flow dryers exhibited the lowest number of impacts, representing the alternative with the lowest environmental risk. However, when technical, economic, and production aspects are considered, hybrid drying is identified as the most suitable option for the cocoa sector, particularly in warm, humid, or rainy regions, as it combines the efficiency of solar drying with the support of artificial energy sources under unfavorable conditions [9], [18]. This flexibility allows for optimized resource use, reduced drying times, and ensured bean quality, making it a sustainable and viable alternative, despite not being the option with the lowest environmental impact [30].

Table 4. Matrix method relating direct and indirect impacts associated with atmospheric pollutants generated by emerging technologies

Technology	Energy / Fuel	Process Stage	Atmospheric Pollutants										Impacts	
			CO	CO_2	NO_x	PAHs	COVs	Soot / visible smoke	$PM_{1,0}$ and $PM_{2,5}$	GHG		SO_2	Direct	Indirect
										CH_4	N_2O			
Samoa type dryers	Firewood	Combustion chamber	a	b	c	d	e	f	g				a. Increase in CO concentration. b. Increase in CO_2 concentration. c. Increase in NO_x concentration. d. Increase in PAHs concentration. e. Increase in VOCs concentration. f. Increase in soot and toxic smoke. g. Increase in the concentration of PM_{10} and $PM_{2.5}$.	a1. Deterioration of public health. b1. Increase in greenhouse gases. c1. Increase in respiratory diseases. c2. Acid rain formation. d1. Increase in respiratory diseases. e1. Increase in greenhouse gases. f1. Loss of landscape visibility.

Technology	Energy / Fuel	Process Stage	Atmospheric Pollutants										Impacts	
			CO	CO_2	NO_x	PAHs	COVs	Soot / visible smoke	$PM_{1,0}$ and $PM_{2,5}$	GHG		SO_2	Direct	Indirect
										CH_4	N_2O			
														f2. Increase in toxic smoke concentration. g1. Increase in respiratory diseases. g2. Increase in cardiovascular diseases.
		Drying chamber				a		b					a. Increase in PAHs concentration. b. Increase in soot and toxic smoke.	a1. Increase in respiratory diseases. b1. Loss of landscape visibility. b2. Increase in toxic smoke concentration.
Tunnel / greenhouse dryers	Solar energy	Grain drying		a			b						a. Increase in CO_2 concentration.	a1. Increase in greenhouse gases.

Technology	Energy / Fuel	Process Stage	Atmospheric Pollutants										Impacts	
			CO	CO_2	NO_x	PAHs	COVs	Soot / visible smoke	$PM_{1,0}$ and $PM_{2,5}$	GHG		SO_2	Direct	Indirect
										CH_4	N_2O			
													b. Increase in VOCs concentration.	b1. Increase in greenhouse gases.
Rotary / drum dryers	Fossil fuels	Gas combustion		a	b				c				a. Increase in CO_2 concentration. b. Increase in NO_x concentration. c. Increase in the concentration of PM_{10} and $PM_{2.5}$.	a1. Increase in greenhouse gases. b1. Increase in respiratory diseases. b2. Acid rain formation. c1. Increase in respiratory diseases. c2. Increase in cardiovascular diseases.

Technology	Energy / Fuel	Process Stage	Atmospheric Pollutants										Impacts	
			CO	CO_2	NO_x	PAHs	COVs	Soot / visible smoke	$PM_{1,0}$ and $PM_{2,5}$	GHG		SO_2	Direct	Indirect
										CH_4	N_2O			
		Rotary drying								a	b		a. Increase in CH_4 concentration. b. Increase in N_2O concentration.	a1. Ozone layer depletion. b1. Increase in greenhouse gases. b2. Ozone layer depletion.
Vertical / mixed-flow dryers	Airflow / thermal energy	Burner chamber	a	b									a. Increase in CO concentration. b. Increase in CO_2 concentration.	a1. Deterioration of public health. b1. Increase in greenhouse gases.
		Drying temperature			a								a. Increase in NO_x concentration.	a1. Increase in respiratory diseases. a2. Acid rain formation.
		Combustion										a	a. Increase in SO_2 concentration.	a1. Acid rain formation.

Technology	Energy / Fuel	Process Stage	Atmospheric Pollutants										Impacts	
			CO	CO_2	NO_x	PAHs	COVs	Soot / visible smoke	$PM_{1,0}$ and $PM_{2,5}$	GHG		SO_2	Direct	Indirect
										CH_4	N_2O			
														a2. Increase in respiratory diseases.
		Dryer operation							a				a. Increase in the concentration of PM_{10} and $PM_{2.5}$.	a1. Increase in respiratory diseases. a2. Increase in cardiovascular diseases.
Hybrid technologies (natural + artificial)	Artificial method	Artificial heating	a	b	c				d	e	f		a. Increase in CO concentration. b. Increase in CO_2 concentration. c. Increase in NO_x concentration. d. Increase in the	a1. Deterioration of public health. b1. Increase in greenhouse gases. c1. Increase in respiratory diseases. c2. Acid rain formation.

Technology	Energy / Fuel	Process Stage	Atmospheric Pollutants										Impacts	
			CO	CO$_2$	NO$_x$	PAHs	COVs	Soot / visible smoke	PM$_{1,0}$ and PM$_{2,5}$	GHG		SO$_2$	Direct	Indirect
										CH$_4$	N$_2$O			
													concentration of PM$_{10}$ and PM$_{2.5}$. e. Increase in CH$_4$ concentration. f. Increase in N$_2$O concentration.	d1. Increase in respiratory diseases. d2. Increase in cardiovascular diseases. e1. Increase in greenhouse gases. f1. Increase in greenhouse gases. f2. Ozone layer depletion.
		Natural method		a					b				a. Increase in CO concentration. b. Increase in the concentration of PM$_{10}$ and PM$_{2.5}$.	a1. Deterioration of public health. b1. Increase in respiratory diseases. b2. Increase in cardiovascular diseases.

These emissions have various causes, including inadequate control of combustion processes, the use of polluting fuels, unregulated environmental conditions during natural drying, and the combination of methods without a prior assessment of their impacts. The lack of a detailed analysis of the emissions generated by each technology represents a barrier to the implementation of more sustainable and less polluting processes in the cocoa industry [23], [26]. Addressing these issues is essential for promoting sustainable agricultural practices and minimizing the environmental impacts associated with cocoa drying. By carefully analyzing the emissions generated by each technology, opportunities for improvement can be identified, and more efficient and less polluting methods can be adopted. This not only contributes to environmental protection, but also improves cocoa quality, strengthening its position in the international market. For example, the implementation of drying technologies that reduce the presence of heavy metals such as cadmium in cocoa beans is important, especially considering European Union regulations that limit their content to 0.8 milligrams (mg) per kilogram (kg). Furthermore, the use of solar energy in drying is an innovation that allows for achieving adequate moisture levels without resorting to fossil fuels, thereby reducing the environmental impact [29]. On the other hand, the manuscript has limitations regarding the quantification of air pollutants, given that the objective of the study was to provide an initial contribution from an academic perspective through a literature review. Furthermore, a meta-analysis was not conducted because the study's operational variables were not systematically controlled.

4. Conclusions

Different cocoa drying technologies exhibit variations in both process efficiency and the generation of atmospheric emissions. This highlights the need to guide implementation toward more sustainable alternatives that optimize product quality while mitigating associated environmental impacts. In this regard, the use of specific energy sources and materials in drying technologies may generate negative environmental effects, particularly on the atmosphere. These impacts are mainly related to the release of compounds resulting from the use of solid, liquid, or gaseous fuels, as well as to the efficiency of combustion systems and the operating conditions during the process.

Samoa-type technology exhibited the highest pollutant load due to the presence of multiple emissions, including greenhouse gases, particulate matter, and toxic compounds. In contrast, tunnel or greenhouse dryers showed the lowest environmental impact, positioning them as the most sustainable alternative with the lowest risk to both human health and the environment. Therefore, it is necessary to optimize cocoa drying processes through more efficient and less polluting technologies, as this stage represents a critical emission point within the production chain. These findings can serve as a basis for the development of mitigation strategies and the adoption of more sustainable practices.

Identifying emerging technologies in the cocoa bean drying process and the associated atmospheric pollutants is a necessary preliminary step toward more rigorous quantification in future research. Therefore, given that solar-based technologies have a lower environmental impact, the use of biomass and fossil fuels results in a higher number of pollutants. Thus, hybrid-drying as an alternative allows for the combination of economic, environmental, and production considerations, as well as the climatic conditions typical of warm, humid, or rainy regions. However, although it combines traditional drying methods, it is not the technology with the lowest environmental impact.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Mauricio Andres Ruiz Ochoa, Abel Rincón Quintero, and Wilmar Leonardo Rondón Romero: study conception and design, draft preparation; Zirley Dayana Ardila Caballero: study conception and design, analysis and interpretation of results; Arly Dario Rincón Quintero and Angel Tlatelpa: study conception and design, draft preparation; Saidy M. Cuadros S. and Sharol A. Naranjo B.: data collection, analysis and interpretation of results. All authors approved the final version of the manuscript.

References

[1] B. Farez-Mendoza, “Exportaciones y crecimiento económico: Análisis para Ecuador, España, Francia y Colombia (1970–2020),” Rev. Económica, vol. 14, no. 1, pp. 79–90, Feb. 2026, https://doi.org/10.54753/rve.v14i1.1678.

[2] E. Ackah and E. Dompey, “Effects of fermentation and drying durations on the quality of cocoa (Theobroma cacao L.) beans during the rainy season in the Juaboso District of the Western-North Region, Ghana,” Bull. Natl. Res. Cent., vol. 45, no. 1, p. 175, 2021, https://doi.org/10.1186/s42269-021-00634-7.

[3] J. F. Vera Chang et al., “Effects of two fermentative methods on cacao (Theobroma cacao L.) Trinitario, induced with Rhizobium japonicum to reduce cadmium,” Rev. Colomb. Investig. Agroindustriales, vol. 10, no. 1, pp. 95–106, Jun. 2023, https://dialnet.unirioja.es/servlet/articulo?codigo=9053385.

[4] A. Therias, A. Rafiee, S. Lhermitte, P. van der Lugt, and R. Lindenbergh, “Integrating radar and multi-spectral data to detect cocoa crops: a deep learning approach,” Remote Sens. Appl. Soc. Environ., vol. 39, p. 101652, 2025, https://doi.org/10.1016/j.rsase.2025.101652.

[5] J. E. Armenta Roncancio, D. F. Olarte Lopez, and J. A. Rincon, “Características físicas, fisicoquímicas y sensoriales de granos de cacao (Theobroma cacao) variedad FTA-4 cosechado en el departamento de Arauca evaluado en condiciones de fermentación y secado variables,” Entre Cienc. e Ing., vol. 17, no. 33, pp. 47–54, 2023, https://doi.org/10.31908/19098367.2829.

[6] M. Santander et al., “Unravelling Cocoa Drying Technology: A Comprehensive Review of the Influence on Flavor Formation and Quality,” Foods, vol. 14, no. 5, pp. 1–39, 2025, https://doi.org/10.3390/foods14050721.

[7] J. Dávila-Guamuro, J. Llanos-Pérez, and L. Cabanillas-Pardo, “Secador solar tipo túnel con microclima auto controlado para Café (Coffea arabica) Honey de alto valor en taza,” Rev. Agrotecnológica Amaz., vol. 2, no. 1, p. e227, Jan. 2022, https://revistaagrotecnologicaamazonia.com/index.php/raa/article/view/227.

[8] E. Somarriba et al., “Rehabilitation and renovation of cocoa (Theobroma cacao L.) agroforestry systems. A review,” Agron. Sustain. Dev., vol. 41, no. 5, p. 64, 2021, https://doi.org/10.1007/s13593-021-00717-9.

[9] P. A. Asante et al., “Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana,” Agric. Syst., vol. 193, p. 103214, 2021, https://doi.org/10.1016/j.agsy.2021.103214.

[10] J. B. Biloa et al., “Influence of cocoa farm age and slope, and shade rate on cocoa soils fertility,” Environ. Challenges, vol. 19, p. 101115, 2025, https://doi.org/10.1016/j.envc.2025.101115.

[11] A. D. Rincon-Quintero, Z. D. Ardila-Caballero, M. Ruiz-Ochoa, C. L. Sandoval-Rodriguez, and L. A. Del Portillo-Valdes, “Environmental impact assessment of a cocoa shell pellet (CSP) combustion system: Effects of integrating an emission filtration system,” Herit. Sustain. Dev., vol. 7, no. 2, pp. 747–770, Jul. 2025, https://doi.org/10.37868/hsd.v7i2.1242.

[12] C. J. Mendoza-Meneses, A. A. Feregrino-Pérez, R. G. Guevara-González, and J. F. García-Trejo, “Implementation of pre-harvest techniques in emerging agroforestry systems to increase the yield of cocoa tree (Theobroma cacao L.),” Heliyon, vol. 9, no. 3, 2023, https://doi.org/10.1016/j.heliyon.2023.e14542.

[13] A. D. Rincon-Quintero, Z. Ardila-Caballero, C. L. Sandoval Rodriguez, P. J. Almanza Merchán, and E.

Fernandez Fernandez, “Primary combustion control of cocoa pod husk pellets: Effects of kaolin additives and air velocity on efficiency and emissions,” Sustain. Eng. Innov., vol. 7, no. 2, pp. 589–604, Dec. 2025, https://doi.org/10.37868/sei.v7i2.id623.

[14] C. Wang et al., “The source of volatile organic compounds pollution and its effect on ozone in high-altitude areas,” Ecotoxicol. Environ. Saf., vol. 286, p. 117221, 2024, https://doi.org/10.1016/j.ecoenv.2024.117221.

[15] K. Sobieraj, S. Stegenta-Dąbrowska, G. Luo, J. A. Koziel, and A. Białowiec, “Carbon Monoxide Fate in the Environment as an Inspiration For Biorefinery Industry: A Review,” Front. Environ. Sci., vol. 10, 2022, https://doi.org/10.3389/fenvs.2022.822463.

[16] A. D. Rincon-Quintero, Z. Ardila-Caballero, M. Ruiz-Ochoca, W. L. Rondon-Romero, L. Mejia-Casadiego, and L. A. Del Portillo-Valdes, “Assessment of the environmental impacts generated by cocoa cultivation biomass in edible mushroom fruiting,” Herit. Sustain. Dev., vol. 6, no. 2, pp. 813–828, Dec. 2024, https://doi.org/10.37868/hsd.v6i2.919.

[17] C. A. Sánchez-Ramos, D. J. Jiménez-Rodríguez, and M. Vargas-Ángeles, “Analysis of the energy performance of cocoa drying equipment in the southeast of Mexico,” Rev. Académica de la Fac. Ing. Univ. Autónoma de Yucatán, vol. 29, no. 3, 2025, https://www.revista.ingenieria.uady.mx/ojs/index.php/ingenieria/article/view/436.

[18] Q. Moseley et al., “Coffee drying processes and their impact on the industry,” Rev. I+D Tecnológico, vol. 20, no. 2, 2024, https://doi.org/10.33412/idt.v20.2.4059.

[19] T. de J. Guzmán-Hernández, J. M. Obando-Ulloa, G. Castro-Badilla, V. Arguelles-Ulloa, and J. Ortiz-Martínez, “Nuevo diseño y aplicación para secadores solares activos y pasivos en la región Huetar Norte de Costa Rica,” Rev. Tecnol. en Marcha, vol. 35, no. 1, pp. 79–89, 2022, https://doi.org/10.18845/tm.v35i1.5319.

[20] J. Pita-Garcia et al., “Impact of combined sun and hybrid drying technologies on cocoa drying process and quality,” Heliyon, vol. 11, no. 4, p. e42884, 2025, https://doi.org/10.1016/j.heliyon.2025.e42884.

[21] N. Y. Castillo-Leon, A. D. Rincon-Quintero, A. A. Mosquera-Clavijo, C. A. Suarez-Lopez, L. A. Betancur-Arboleda, and L. del Portillo-Valdes, “Energy and exergy evaluation in a densified biomass burner using cocoa shells, intended for air heating for the artificial drying of food,” Sustain. Eng. Innov., vol. 6, no. 2, pp. 309–326, 2024, https://doi.org/10.37868/sei.v6i2.id385.

[22] A. Tlatelpa Becerro et al., “Drying Kinetics of Leucaena esculenta Seeds Using a Solar Dryer,” Energies, vol. 17, no. 24, p. 6364, 2024, https://doi.org/10.3390/en17246364.

[23] V. V. Tyagi et al., “Sustainable growth of solar drying technologies: Advancing the use of thermal energy storage for domestic and industrial applications,” J. Energy Storage, vol. 99, p. 113320, 2024, https://doi.org/10.1016/j.est.2024.113320.

[24] I. A. Santos et al., “Enhanced physicochemical and antifungal properties of starch bionanocomposites reinforced with nanocellulose and functionalized with AgNPs derived from cocoa bean shell,” Int. J. Biol. Macromol., vol. 294, p. 139262, 2025, https://doi.org/10.1016/j.ijbiomac.2024.139262.

[25] J. W. Hawkins et al., “Low-emissions and profitable cocoa through moderate-shade agroforestry: Insights from Ghana,” Agric. Ecosyst. Environ., vol. 367, p. 108961, 2024, https://doi.org/10.1016/j.agee.2024.108961.

[26] D. Rodríguez-Ortiz, A. Y. Alanis, Á. T. Becerro, J. E. Bretado, J. D. Rios, and E. C. López-Vidaña, “Prediction of Drying Kinetics and Microclimate Conditions in a Tunnel-Type Solar Dryer Using Multilayer Perceptron Neural Networks,” Processes, vol. 14, no. 4, p. 675, 2026, https://doi.org/10.3390/pr14040675.

[27] A. Tlatelpa Becerro, R. Rico Martínez, E. C. López-Vidaña, E. Montiel Palacios, C. Torres Segundo, and J. L. Gadea Pacheco, “Dynamic Behavior Forecast of an Experimental Indirect Solar Dryer Using an Artificial Neural Network,” AgriEngineering, vol. 5, no. 4, pp. 2423–2438, 2023, https://doi.org/10.3390/agriengineering5040149.

[28] N. Konar, M. Fidan, I. Palabiyik, I. Atalar, and O. S. Toker, “Comprehensive life cycle assessment of cocoa and chocolate supply chains: Environmental sustainability perspectives,” Trends Food Sci. Technol., vol. 169, p. 105543, 2026, https://doi.org/10.1016/j.tifs.2026.105543.

[29] F. Mariatti, V. Gunjević, L. Boffa, and G. Cravotto, “Process intensification technologies for the recovery of valuable compounds from cocoa by-products,” Innov. Food Sci. Emerg. Technol., vol. 68, p. 102601, 2021, https://doi.org/10.1016/j.ifset.2021.102601.

[30] S. Kalambe and S. Guhe, “Foam mat drying of perishable products: a critical review of process parameters, product quality, and sustainable prospects,” Sustain. Food Technol., vol. 4, no. 1, pp. 133–152, 2025, https://doi.org/10.1039/d5fb00203f.