Energy Use and Greenhouse Gas Emissions in Selected Tea Factories in Kenya

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Abstract

Tea sector is a major contributor to Kenya's economy through foreign exchange via export. However, extensive amount of energy is required to produce one kilogram of tea, making tea processing energy-intensive. Comparing greenhouse gas emissions from different types of energy consumed in tea factories is imperative to enable policymakers make informed intervention in emission reduction. Reducing greenhouse gas emissions in tea factories is one of the pathways to meeting Kenya's nationally determined 32% reduction of carbon emissions by 2030 and commitment to the Paris Agreement. This paper assesses greenhouse gas emissions from different sources of energy used in four tea factories in Kenya. The Intergovernmental Panel on Climate Change emission factor is used to calculate the total emissions of each type of energy used for 5 years. Life cycle assessment using simapro software is used to assess the specific compound causing the emission. The findings reveal that the 5-year greenhouse gas emissions by biogas, solar, wood, briquettes, and electricity are 336,111, 7,108, 20,201.06, and 1,338.28 kg CO_2/kWh, respectively. Firewood has the highest concentration of carbon dioxide, while solar energy has the least. Analysis of variance confirms significant difference ($0.05>p=0.0272$) in greenhouse gas emissions from the different energy sources. Post-hoc analyses shows a significant difference in emissions between solar and firewood ($p<0.0125$) and no significant difference between other sources of energy. Sustainability in the tea sector can be achieved through switching to macadamia

briquettes as a source of thermal energy and a combination of electricity and solar for electrical energy.

Keywords: Greenhouse gas emissions, energy mix, life cycle assessment, tea factories, Kenya

1. Introduction

Tea is an essential beverage globally and ranks second among the most consumed drinks, with water being the first [1]. China is the leading tea producer globally, followed by India, Kenya, Vietnam, and Sri Lanka [2]. Global tea production was 6.29 million tons in 2020, showing an increase of 3.5% in 2021 [3]. Energy consumption globally is constantly increasing, resulting in increased emissions of gases and global warming [4]. Growing concerns about emissions are attributed to the use of fossil fuels as sources of energy [5]. The burning of fossil fuels raises CO_2 and greenhouse gas (GHG) levels in the atmosphere, which leads to increased global climatic changes, especially warming [6]. The continuous use of fossils leads to increased concentration of carbon gases in the atmosphere by 35%, which increases the earth's temperature [6]. Energy-related CO_2 emissions globally are estimated to be 7% higher in 2030 due to increase in demand for energy, which is estimated to be 6% in 2030 [7]. Due to the rise in global warming, emissions of GHG, fluctuating oil prices, and rising electricity demand in developing countries, alternative energy solutions are required [8]. Using alternative energy resources like renewable energy helps reduce the carbon content in the atmosphere, hence reducing the problem of global warming [9]. The use of solar energy as a source of electricity results in less environmental impact [10]; whereas the consumption of biogas as an alternative fuel source reduces CO by 46% and CO_2 by 88.27% [11]. Agricultural activities contribute between 10% and 12% of the world's CO_2 emissions [12]. Energy combustion while drying tea leads to emission of GHG like CO_2 and unburnt particulates into the atmosphere [9]. Tea factories in Kenya still consume fuel wood extensively [13]. The burning of wood energy sources leads to the release of CO_2 absorbed during a tree's life cycle, which impacts the environment by contributing to climate change [14]. Wood waste can cause environmental footprints, especially in the boilers used in industries where the equipment used for the operation emits more than 32kgCO_2 eqMg^{-1} of the combusted wood from ash deposits [15]. Carbon emissions significantly vary from country to country, ranging between 2.51 and 5.41kgCO_2/kg of made tea (MT) [16]. For instance, the specific CO_2 emission to produce 1 kg MT is 2.49 kg CO_2 /kg in Sri Lanka, 2.15 kg CO_2 /kg in India and 2.86 kg CO_2 /kg in Vietnam [16]. A research by Niyonzima *et al.*estimated a total annual emission from the tea life cycle in Rwanda as 365.31kgCO_2eq/kg MT, with the most significant emissions coming from nitrous oxide (N_2O) equating to 0.696kgCO_2eq/kg MT [17]. Among the three GHGs, the key contributors to global warming are CO_2 (98%), N_2O (1.3%), and methane (CH_4) gas (0.7%) [18]. The GHG emissions in tea processing are obtained using data from production and utilities, which include the amount of energy used in tea processing [19].

2. Material and Methods

2.1. Description of Study area

The paper is based on four tea factories located in different counties of Kenya. The tea factories are Chemogondany in Kericho, Kitumbe in Bomet, Kagwe in Kiambu, and Makomboki in Murang'a County. Kagwe is located at 1°00'17"S 36°43'35"E, Makomboki at 0°99'26"S 37°26'19"E, Chemogondany at 0°28'45"S 35°18'30" E, and Kitumbe at 0°24'53"S 35°18'30"E (Figure 1).

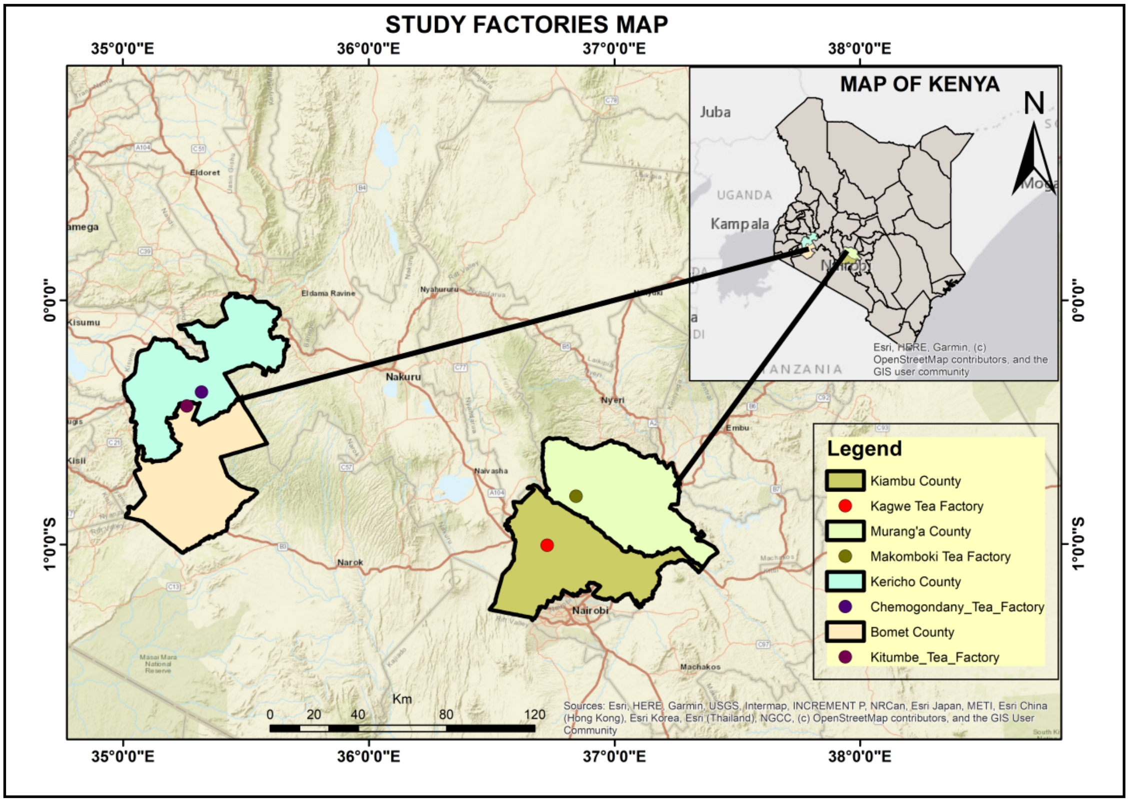

Figure 1: Study factories location [10]

2.2 Data Collection and analysis approaches and techniques

The paper is based on a descriptive-comparative research design, which helps in determining the relationship between more than one variable [20] One-on-one survey interviews were conducted to get information about energy sources and usage in the tea factories. The major source of primary data was interviews with tea factory managers and technical heads in charge of tea processing. The secondary data was collected from tea factory reports, records, systems, and historical operational data. The data include the tea factories' energy consumption of different energy sources (electricity, solar, biogas, briquettes, and firewood) for a 5-year period.

The paper uses the Intergovernmental Panel on Climate Change (IPCC) impact factor for each energy source to get the total GHG emissions [21]. Simapro 7.1 software and Eco-indicator 99 assessment method were used to identify the specific elements of the emissions. The emission model is run to get the specific GHG based on each system's material or energy requirement. The Eco-indicator 99 method was utilised since it combines emissions from a single high-level score and the lowest level single score with carbon capture storage (CCS), which has been employed before [22]. Eco-indicator 99 is a damage-oriented method that focuses on impacts on three main categories: ecosystem quality, human health, and resources. For the Eco-indicator 99 method, "E" is the eco-indicators score for materials and processes used in the life cycle assessment (LCA) resulting in emissions [23]. All the units are then combined to form a point (Pt), which is the sum of the total impacts [24]. The point is the total environmental load expressed as a single score of characterization normalization, damage assessment and weighing; combined as one [24]. The reliability and validity of the LCA process was done through the definition of system boundaries. A system boundary curve model of the LCA was developed, and the threshold rule and judging satisfied the research requirements. Environmental, temporal, and technical dimension criteria were used to limit the LCA boundaries as recommended by [25]. The principal method employed in defining the concept of the system was process tree (PT). The method was valid as it includes the process involved and the transportation processing production and disposal of the energy sources. The boundaries between technological system and nature were determined by selection of the energy sources and their raw materials. For example, raw materials (spent leaves) for biogas, macadamia nuts for briquettes, and species of tree for firewood. Additionally, for waste disposal, landfills were included in the technological system inventory. Geographical area was defined in the system in order to get the required results which leads to inclusion of transportation and the sensitivity of the environment to the pollutants. Time horizon of years was also defined in the system as to model the impacts over the specifies period of time.

The paper covered the GHG emissions associated with the use of energy in tea production and processing. Energy sources for the production of thermal energy used for drying tea in tea factories were the purchased electricity from the national grid, biogas, solar, firewood and briquettes. The system boundary covered the energy used during the production and processing of tea, withering, rolling, oxidation, and drying. The functional units were the carbon emissions per kg of dry tea (kg CO_2eq kg). GHG inventory was associated with energy usage during the production and processing of tea. The emissions of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), Nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulates associated with tea production and processing were obtained from simapro modeling of emissions.

2.3 Governing equations and principles

The emission factor for different energy uses in this paper is based on the IPPC [21] standard emission factor (Table 1).

Table 1: IPCC standard emission factors for different energy [21]

Energy type	Standard emission factor (tCO_2/MWh)
Wood	0.2015
Solar PV	0.035
Electricity	0.00073576632
Biogas	0.098
Primary solid biomass	0.180
Industrial waste	0.257

The emission factor (Table 1) was derived [27] as follows:

$$EFEL,m,y = \frac{\sum i\ FCi,m,y \times EFCO2,i,y \ \times NCVi,y}{EGm,y} \quad (1)$$

In which:

$EF_{EL,m,y}$	=	The emission factor for of unit of power *m* per year *y* (t CO_2/MWh)
$FC_{i,m,y}$	=	Total fuel source *i* consumed by unit power *m* per year *y* (volume or mass unit)
$EF_{CO2,i,y}$	=	CO_2 emission factor of fuel source or type *i* in year *y* (t CO2/GJ)
$NCV_{i,y}$	=	Energy content (Net calorific value) of fuel source or type *i* per year *y* (volume, mass or GJ)
$EG_{m,y}$	=	Net electricity quantity generated and distributed to the grid by power unit *m* per year *y* (MWh)
m	=	Combined all power units giving power to the grid in year *y*
i	=	All fuel sources or types burnt in power unit *m* per year *y*

Greenhouse gas emission was determined as follows:

$$GHG\ Emissions\ (kgCO2e/kg\ of\ tea = Emissions\ factor \times\ amount\ of\ material\ used \quad (2)$$

For analysis purposes, it was assumed that all the thermal and electric energy are utilized directly in production. The following conversions were used for comparison and analysis purposes:

- 1m^3 of firewood produces the equivalent of 1750kWh while 1 unit of electricity costs 0.16 USD/kWh. 1kWh of energy is equivalent to 3.6 mega joules (MJ) of thermal or electrical energy from sources like solar, biogas, wood fuel, or briquettes energy and 40.28MJ/L of fuel oil.

- 1m^3 of firewood is equivalent to1800Kg of steam/m^3, 1 kg of bagasse containing 30% moisture content (MC) is equivalent to 12.6MJ energy, and 1kg of macadamia husks is equivalent to 15.1MJ. 29.9Gj/t MT.

2.3 Data analysis

Data from tea factories' energy bills and survey interviews were used to derive the total GHG emissions for five years using equation 2. Per impact category emission was modelled using simapro software and Eco-indicator 99 method based on the IPCC emission factor and emission to the air, followed by normalization to allow comparison of the impacts to the system-referenced values as recommended by Helder and Bruno [28]. Analysis of variance was done to determine whether there is a significant difference between the GHG emissions of different energy sources. Post-hoc analysis was also performed to determine multiple comparison between the factories' energy sources.

3. Results and Discussion

3.1 Consumption of biogas energy and greenhouse gas emission by Chemogondany tea factory

Production of biogas by Chemogondany tea factory is through anaerobic digestion in a digester with 1700m^3 holding capacity that can hold up to 1600 tonnes of the mixture. The materials used as feedstock are spent waste leaves from the tea factory and a small amount of septic waste. The feeding stock materials are preferred as they are readily available, environmentally friendly, and are a sustainable way of managing waste. On average, 625m^3 of gas is produced per day, and the volume of the gas depends on the amount and nature of the substrate fed into the digester.

The emission factor for biogas is 0.098tCO_2/MWh (Table 2), which is slightly lower than that of wood and briquettes. The total amount of GHG produced for five years for biogas production in the factory is 336,111tCO_2/MWh (Table 2)**.** Sejahrood et al. [11] indicated that biogas energy could reduce carbon emissions by 40-88% compared to firewood. However, this study shows a reduction in carbon emissions of 34.5% compared to firewood, with the difference attributed to the different nature of biogas feedstock. Additionally, wood combustion produces heat and emission in the form of organic vapours, water, gases, and particles, resulting in an increased emission factor.

Table 2: Biogas production emissions by Chemogondany factory

Year	Energy produced (kWh)	Emission factor	GHG emission (tCO_2equivalent)
2016	826,082	0.098	80,956.04
2017	470,948	0.098	46,152.90
2018	696,740	0.098	68,280.52
2019	791,676	0.098	77,584.25
2020	644,259	0.098	63,137.38
Total	3,429,705		336,111

Research by Manyuchi and Mbohwa [29] reported CH_4 gas as the highest composition in biogas production, ranging from 60-65% followed by CO_2 that range from 30-35%. This study (Figure 2) indicates different substances causing emissions, with 52% caused by N_2O and 22% by CO_2. The difference between this study and that of Manyuchi and Mbohwa [29], is the difference in the feedstock of the biogas plant, which generates different emission substances. The other substances causing GHG emissions are CO_2, SO_2, particles from mobile and stationary objects, and arsenic.

The total compartmentalization of emissions to environmental for biogas energy is 0.038233points of environmental load.

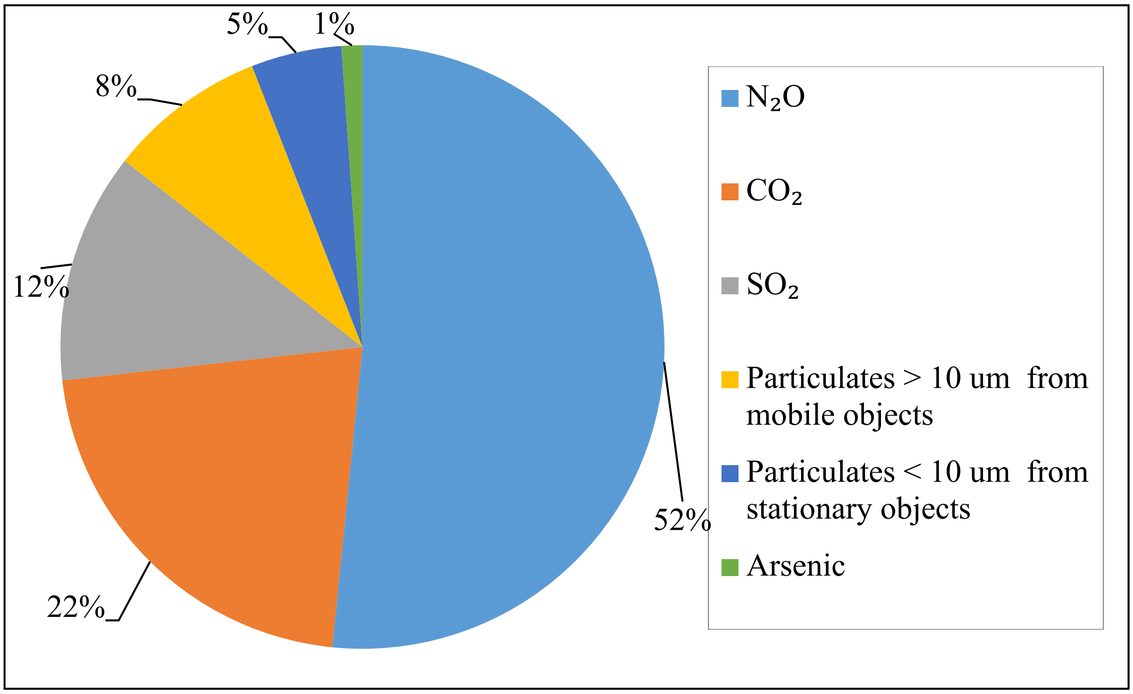

Figure 2: Biogas production emission damage assessment by Chemogondany factory

3.2 Solar energy use and greenhouse gas emission by Kitumbe tea factory

The solar system at Kitumbe factory has a total of 120 solar panels, each 1.5m by 1m in dimension. The panels are connected directly to the power grid, and the solar system generates no waste materials. The direct current solar panels have an output of 30kWh per day, indicating that one solar panel produces approximately 0.25kW of electricity per day. Table 3 shows the energy production from solar energy has an emission factor of 0.035 tCO_2/MWh, which is the lowest among other fuel sources except electricity since solar panels are less carbon-intensive sources of energy. The total amount of GHG emissions from the solar plant in the five years is 7108 tCO_2/MWh (Table 3). The use of solar energy in tea processing minimizes carbon emissions and health hazards, as reported by Magu, Kiragu and Mwenda [30], which is similar to what this study indicates.

Table 3: Solar energy emissions by Kitumbe Factory

Year	Solar energy (kWh)	Emission factor	GHG emissions (tCO_2equivalent)
2016	45,815	0.035	1603.525
2017	37,151	0.035	1300.285
2018	40,612	0.035	1421.42
2018	39,452	0.035	1380.82
2020	40,060	0.035	1402.1
Total	203,090		7,108

Figure 3 shows the emission damage assessment per substance, where N_2O is the major contributor to GHG at 44% and CO_2 at 29%. A study by Niyonzima *et al.* [17] reported a high concentration of CO_2, equating to 0.696kgCO_2eq/kg emission in a tea factory in Rwanda, followed by NO_2, unlike this study's result that shows N_2O having a higher concentration. The difference is the type of solar technology used; in this study, it is a grid-connected system while the compared study is a stand-alone system. The total compartmentalization of emissions to environmental for solar energy is 2.77E-07points of environmental load.

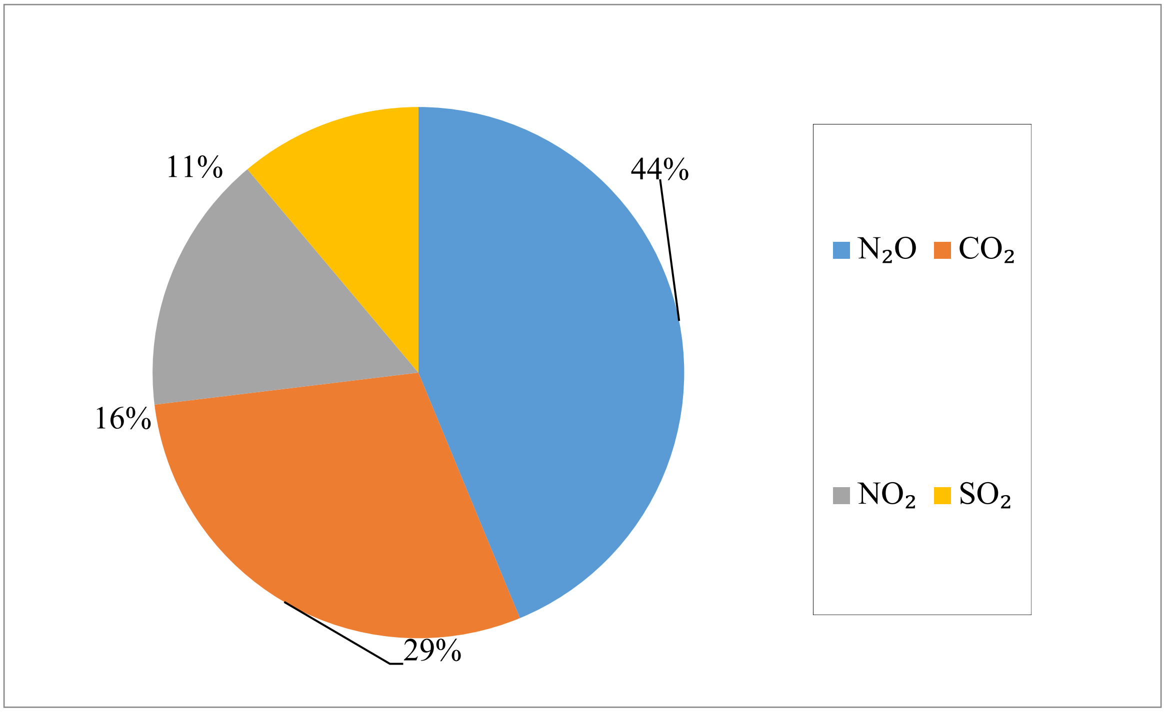

Figure 3: Kitumbe factory solar emission damage assessment

3.3 Briquettes and firewood energy consumption and emission by Kagwe tea factory

Kagwe tea factory (Table 4) consumes firewood, briquettes, and electricity in their tea processing. Over the five-year period under review, firewood produced a total of 20,201.06 tCO_2/MWh of emissions while briquettes produced 111.18 tCO_2/MWh of GHG. Firewood energy consumption has a high emission compared to briquettes, with a similar finding reported by Morris [31].

Table 4: Firewood and briquette energy emissions by Kagwe tea factory

Year	Firewood energy (tCO_2/MWh)	Briquettes emissions (tCO_2equivalent)
2016	3602.471405	0
2017	3165.29096	0
2018	4241.10349	1.14855
2019	4028.015225	13.39572

2020	5164.18305	96.641415
Total	20,201.06	111.185685

Emission damage assessment per substance for firewood consumption by Kagwe factory (Figure 4) shows CO_2 from burning of fossils having the highest concentration with 45% followed by CO_2 from biogenic substances with 32%. Other substances causing GHG emissions are particulates, SO_2, and N_2O, and NO_2. Similar results were reported in the research by Taulo and Sebitosi [18] in Malawi, where CO_2 had the highest concentration over other substances. The total compartmentalization of emissions to environmental for solar energy is 0.104771 points of environmental load.

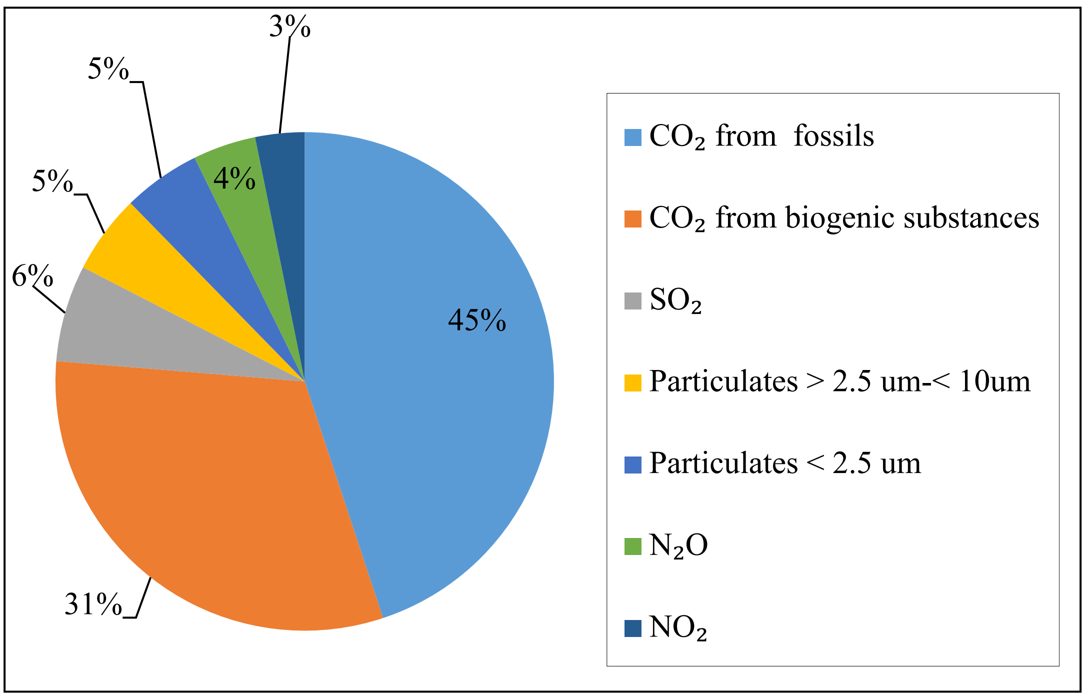

Figure 3: Firewood emission damage assessment of Kagwe Factory, obtained from simapro modelling of gas emissions

3.4 Macadamia briquettes and wood energy consumption and emission by Makomboki tea factory

Makomboki tea factory uses firewood, macadamia briquettes, wood briquettes, and electricity for their tea processing. Wood briquettes emitted a total of 364.37 tCO_2/MWh emissions over the five-year period (Table 5). Macadamia briquettes had a total emission of 1,337.26 tCO_2/MWh over the same period. The emission factor for briquette fuel is slightly lower than that for wood fuel (Table 1), but macadamia briquettes are consumed in large quantities. The total GHG emissions from the firewood fuel are 16,222.76 tCO_2/MWh. The increase in GHG emission from wood consumption is due to the emission of waste material from wood combustion and ash materials. Similar findings were reported by Morris [31].

Table 5: Wood and macadamia briquette emissions in Makomboki tea factory

	Emissions (tCO_2equivalent)		
Year	Wood briquettes	Macadamia briquettes	Firewood
2016	10.45	722.67	1,006.09
2017	54.92	570.76	1,443.55
2018	185.39	18.07	4,113.42
2019	94.56	23.15	4,894.84
2020	19.02	2.59	4,764.87
Total	364.37	1,337.26	16,222.76

Emission damage assessment per substance (Figure 5) indicates CO_2 biogenic has the highest concentration at 73%. The other substances causing GHG emission are particulates, CO_2 from biogenic matter, and SO_2 and CO_2 from fossils. A similar trend was reported by Morris [31], with CO_2 having the highest substance concentration. In contrast, N_2O was not found in the substance, but instead in particulate matter. The results show that wood briquettes emit different substances from those emitted by firewood.

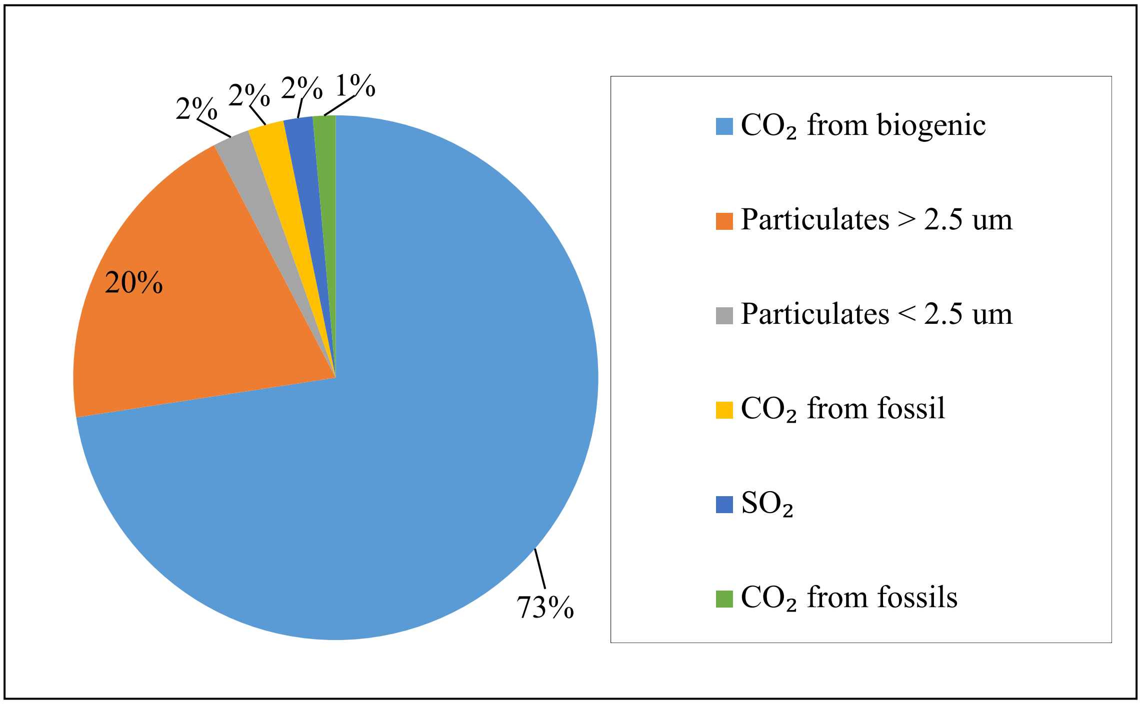

Figure 4: Makomboki factory briquette emissions damage assessment

3.5 Electricity emissions by the four tea factories

Kitumbe factory produced 17,547,791.29 kg CO_2/kW (Table 6) of GHG emissions due to electricity consumption, which is higher than the other three factories. The emission factor for electricity is 0.73576632 kg CO_2/kWh, which is lower than that of biogas, briquettes, solar, and firewood. Kagwe tea factory recorded the lowest GHG gas emission of 11,155,450.56 kg CO_2/kWh as a result of electricity consumption for a period of 5 years. Chemogondany tea factory recorded GHG emissions slightly lower than Kitumbe factory while Makomboki factory recorded GHG emissions slightly higher than Kagwe but lower than Chemogondany factory. Liang *et al*. [32] reported a higher GHG emission by tea processing, contrary to this study, as they recorded

28,750,000 kg CO_2/kWh in five years. The variation in the results is because of the different amounts of energy used.

Electricity damage assessment (Figure 6) indicated CO_2 from fossils as the significant damage resulting from electricity use with 54%. There is a similar concentration of substances for damage assessment across all four factories. Similar results were reported by Liang *et al*. [32] on the substances causing GHG through electricity consumption.

Table 6: Electricity emissions by the tea factories (tCO2equivalent)

Year	Chemogondany factory emission	Kitumbe factory emission	Kagwe factory emission	Makomboki factory emission
2016	3,345,399.22	3,722,471.37	2,308,476.39	2,257,361.97
2017	2,903,386.87	2,913,518.37	2,018,037.05	2,321,329.49
2018	3,139,231.61	3,467,295.10	2,036,748.32	2,566,887.09
2019	2,816,116.89	3,391,769.42	2,099,501.10	3,089,763.10
2020	5,343,656.67	4,363,626.23	2,692,687.68	2,833,706.86
Total	17,547,791.29	17,858,680.50	11,155,450.56	13,069,048.52

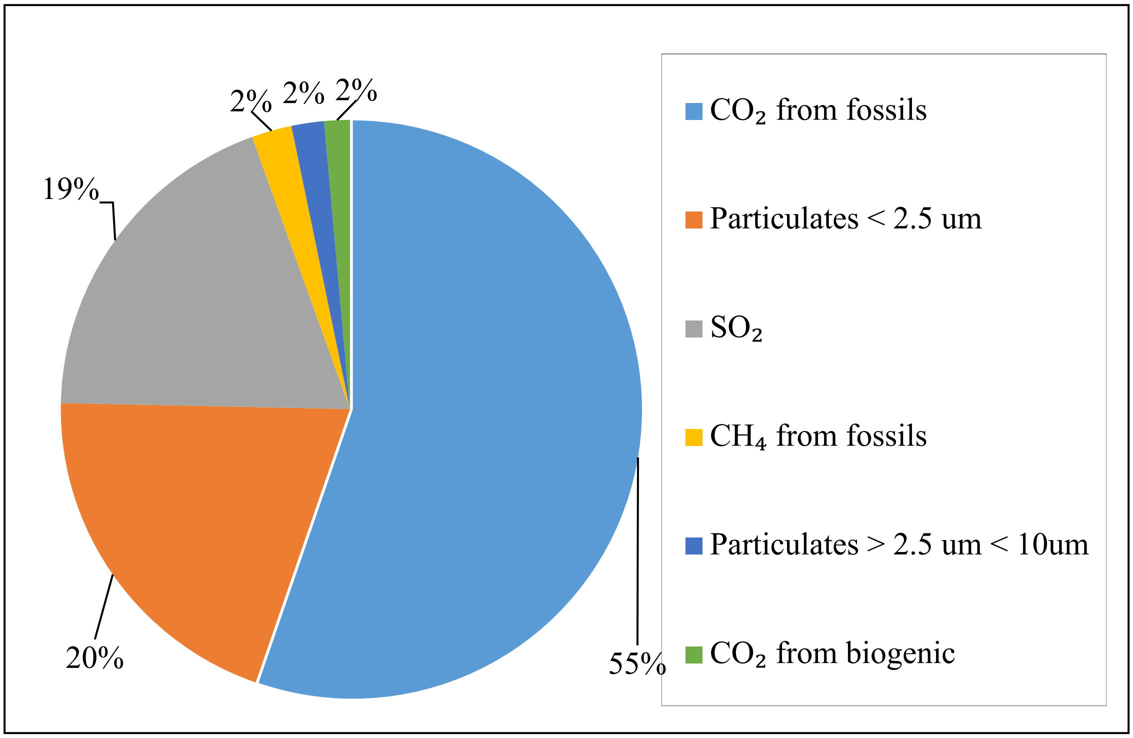

Figure 5: Electricity emission damage assessment by the four tea factories

3.6 Emission Comparison Analysis

The total 5-year GHG emissions by the four tea factories reveal that firewood has the highest emission of 20,201.06 tCO_2/MWh (Table 7) compared to biogas, solar, and briquettes that had 336,111 tCO_2/MWh, 7,108 tCO_2/MWh and 1,338.28 kg CO_2/kWh, respectively. Electricity has the lowest emission of all other sources due to its lower emissions factor. Regarding per-substance emission, wood has the highest concentration, with CO_2 being the highest with 0.040286 points of total environmental load for five years. Biogas production is the second with 0.038233 points of environmental load, and briquettes are the third with 0.029378 points. Solar energy has the lowest emissions with 2.77E-07 points of environmental load, which is lower than other forms of energy, including electricity. The high emission of wood energy is due to the loss of biomass by the felling of trees and the emission of ash, which is the waste product from wood consumption. The lower emission of solar energy is due to its lower emission factor, coupled with its little used in tea processing. Similar findings were reported by Morris [31], stating the same reasons for the wood energy emission.

Table 7: Energy emission damage assessment comparison for the four tea factories in Kenya obtained from LCA Model

No	Substance	Makomboki Wood	Chemogondany Biogas	Kitumbe Solar	Kagwe Briquettes	Chemogondany Electricity	Makomboki Electricity	Kagwe Electricity	Kitumbe Electricity
	Total of all compartments	0.104771	0.038233	2.77E-07	0.029378	0.003291	0.002674329	0.002089	0.00335
	Total of airborne emission	0.092087	0.064068	2.25E-07	0.068679	0.003236	0.002629652	0.002054	0.003294
	Remaining airborne emission	0.000161	0.043524	2.25E-07	0.068295	0.003224	0.00261985	0.002047	0.003282
1	Carbon dioxide	0.040286	0.01168	6.59E-08	0.02495	0.0018751	0.0002002	0.0011913	0.0019095
2	Sulfur oxides (SO_2)	0.028576	0.00324	2.55E-08	0.000508	0.0006251	0.0005073	0.0003971	0.0006365
3	Particulates < 10 um (stationary)	0.014693	0.001272	x	0.000637	0.000658	0.000534	0.000418	0.00067
4	Methane	0.004097	x	x	x	0.0000658	0.0000534	0.0000418	0.0067
5	Particulates > 10 um (mobile)	0.002024	0.00222	x	0.005582	x	x	x	x

6	Carbon monoxide	0.000797	x	x	x	x	x	x	x
7	Nitrogen oxides (N_2O, NO_2)	0.000511	0.01354	1.454194 E-8	5.55E-05	1.02E-06	8.27054E-07	6.46E-07	1.04E-06

Key: x Indicates less significant damage as a result of compound release. The values are expressed as the total environmental load as a result of emission modelling

The analysis of variance (ANOVA) on the significance of greenhouse gas emission (Table 8) of different types of energy source consumption demonstrates that the p value (0.0272) is less than the significant level ($p<0.05$) whereas the F value (3.762492) is greater than the F-critical value (3.098391). The results confirm that there is a significant difference in greenhouse gas emissions attributed to different energy uses by the four tea factories. The mean greenhouse gas emission between the four tea factories over five years is different.

Table 8: Comparison of greenhouse gas emissions for the four tea factories in Kenya

Factory Emission	Years	Sum	Average	Variance
Chemogondany	5	17547791	3509558	1.09E+12
Kitumbe	5	17858681	3571736	2.82E+11
Kagwe	5	11136739	2227348	8.18E+10
Makomboki	5	1.43E+08	28510188	7.72E+14

Years - the number of years under review in each group, Sum - the total of the values in each tea factory over the 5-year period, Average - the average value in each group (tea factory), variance - the variance of the values in each factory

Table 9: ANOVA on greenhouse gas emissions for four factories in Kenya

Variation	SS	Df	MS	F	P-value	F crit
Between Groups	2.43E+15	3	8.09E+14	4.183657	0.022972	3.238872
Within Groups	3.09E+15	16	1.93E+14			
Total	5.52E+15	19				

Key: SS Summation of squares, MS - Mean of squares, Df - Degree of freedom, F - Variation within and samples, P - the level of significance, F crit - Significance critical level

Post-hoc analyses to determine multiple comparison show that there is no significant difference ($p>0.0125$) between the GHGs emission between biogas, briquettes and solar sources of energy. However, there is a significant difference ($p>0.0125$) between GHG emissions in the use of solar and firewood as sources of energy. This means that the use of solar energy to boost the national grid leads to reduced GHG emissions; whereas the use of firewood leads to more GHG emissions.

Table 10: ANOVA significant level and post-hoc test (Bonferroni correlation) value

Test	Alpha
ANOVA	0.05
Post-Hoc Test (Bonferroni corrected)	0.0125

Table 11: Post-hoc significance test between emission of different energy sources by tea factories

Post-hoc test (Bonferroni correlation)		
Groups	p-Value (T-Test)	Significant?
Chemogondany vs Kitumbe Factory	0.908562444	No
Chemogondany vs Kagwe Factory	0.029527546	No
Chemogondany vs Makomboki Factory	0.079187019	No
Kitumbe vs Kagwe Factory	0.001070066	Yes
Kitumbe vs Makomboki Factory	0.079672771	No
Kagwe vs Makomboki Factory	0.067320725	No

4. Conclusion

This paper show that the total greenhouse gas (GHG) emission for biogas production to produce 3,429,705 kWh of electricity is 336,111 tCO_2/MWh, with the substances causing damage to the environment being carbon dioxide (CO_2) with 73% emission to the air, followed by ammonia gas (CH_4) with 20%, and the lowest emission is particulate matter. Solar energy emits 108 tCO_2/MWh of GHG to produce 203,090 kWh of electricity, with the low emission attributed to low emission factor of solar technology and its small size. The total emission of macadamia and wood briquettes to generate energy equivalent to 7,429,240 kWh of electricity is 1,337,263.2 tCO_2/MWh, with CO_2 being the highest damage to the environment. Emission by use of firewood to produce heat equivalent to 100,253 kWh of electricity is 20,201 tCO_2/MWh, with the substance causing damage to the environment most being CO_2 from fossil fuels and lowest being nitrous dioxide (N_2O.

The paper concludes that there are differences in GHG emission by different energy source ($p>0.05$) from analysis of variance test. Post-hoc analyses to determine multiple comparison show that there is no significant difference ($p>0.0125$) between the GHGs emission between biogas, briquettes and solar energies. However, there is a significant difference ($p>0.0125$) between GHG emissions by the use of solar and firewood as the sources of energy. The difference is attributed to the higher emission factor of firewood and the lower emission factor of solar technology.

The paper contributes to Sustainable Development (SDG) 17 on affordable and clean energy, which targets to increase the use of renewable energy by switching to energy sources with less GHG emissions. Tea factories can contribute to the attainment of Kenya's nationally determined 32% reduction of carbon emissions by ensuring energy sustainability in tea factories. Energy sustainability in tea sector can be achieved through GHG reduction by switching to macadamia briquettes as a source of thermal energy and a combination of electricity and solar energy for electrical energy. Biogas energy from tea waste can be used in areas where there is less solar intensity. Therefore, there is need for the government to give clear guidelines on the type of energy to be used in tea factories.

Abbreviation

ANOVA	Analysis of Variance
CCS	Carbon Capture Storage

CH_4	Methane gas
CO_2	Carbon dioxide
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
kgCO2/kWh	Kilogram of carbo dioxide per Kilowatt hour
$kgCO_2eq/kg$	Kilogram of Carbon dioxide equivalent per Kilogram
KWh	Kilowatt hour
KWh/M^2	Kilowatt hour per Meter Squared
LCA	Life Cycle Assessment
M^3	Cubic metres
MC	Moisture Content
MJ/kg MT	Mega Joules per Kilograms Made Tea
N_2O	Nitrous oxide
NACOSTI	National Commission for Science, Technology and Innovation
NO_2	Nitrogen dioxide
PV	Photovoltaic
SDG	Sustainable Development Goal
SO_2	Sulphur Dioxide
tCO2/MWh	Tonnes of carbon dioxide per Megawatt hour

Ethical Approval

Consent to research energy use and greenhouse gas emissions by selected tea factories in Kenya was sought and granted by National Commission for Science, Technology and Innovation

(NACOSTI), permit number 836833 through the issuance of a research permit.

Data availability

The data to support and conclude the findings of this article are included within the article (and its additional files)

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

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Energy Use and Greenhouse Gas Emissions in Selected Tea Factories in Kenya

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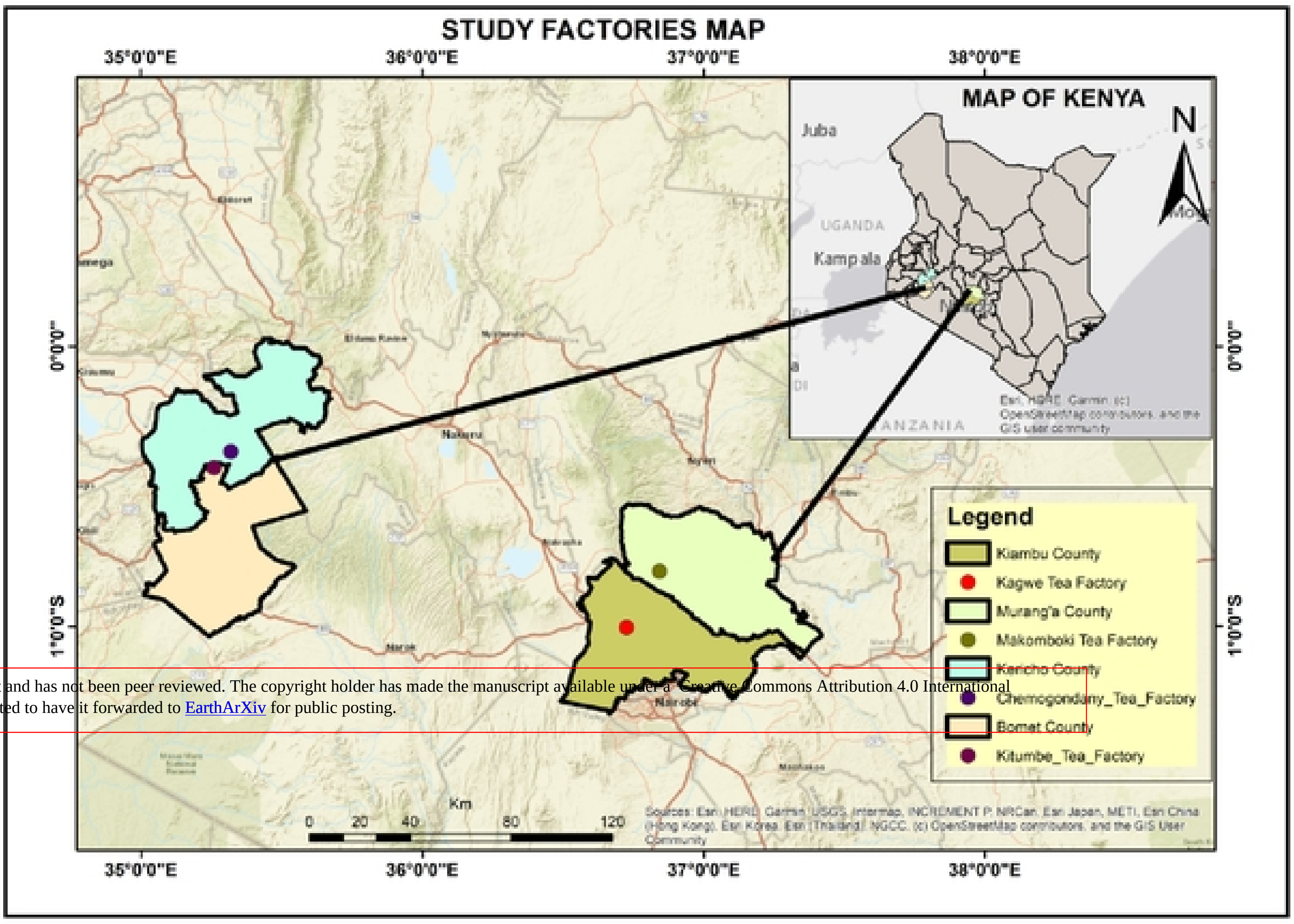


Figure 1: Study factories location [10]

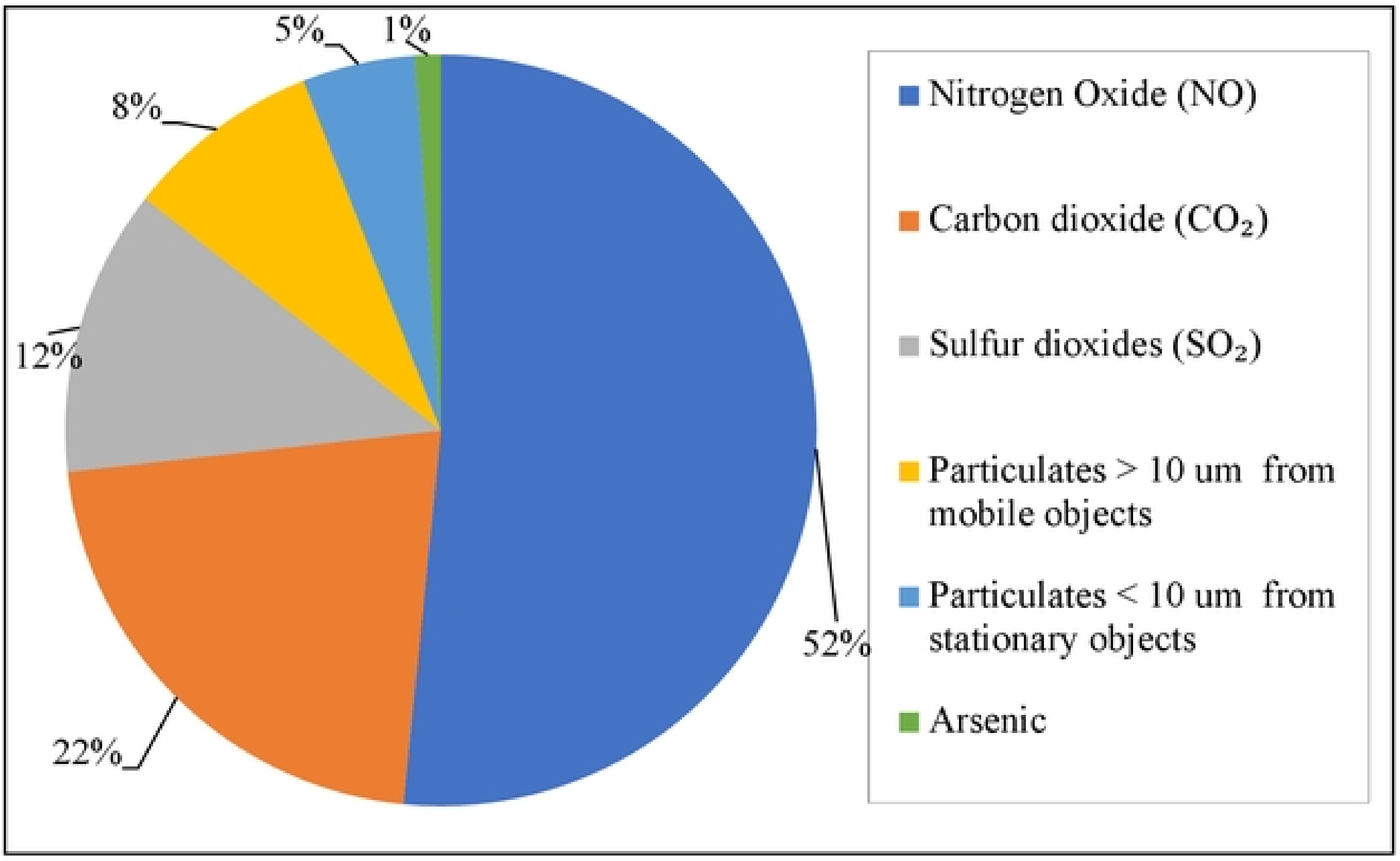
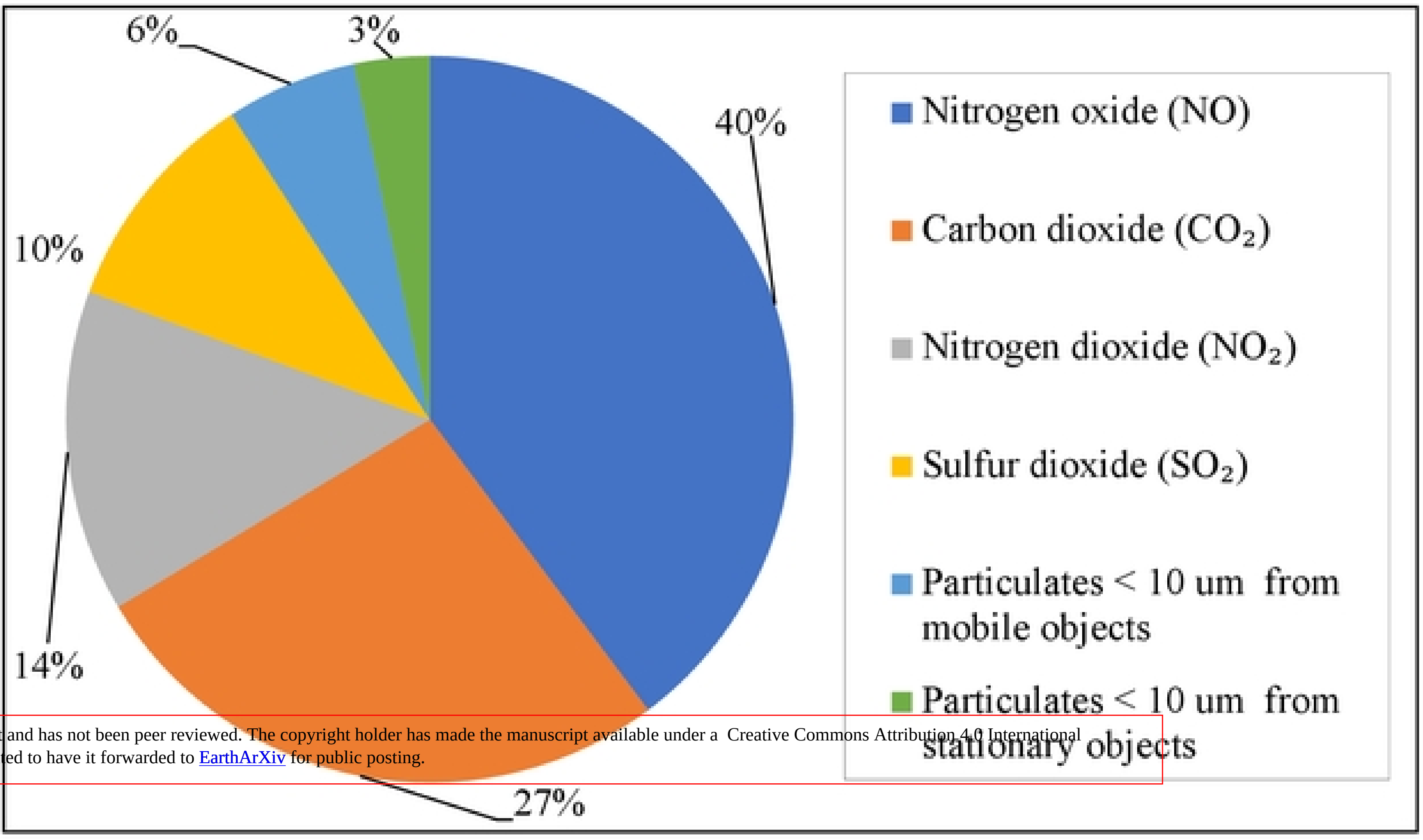


Figure 2: Biogas production emission damage assessment by Chemogondany factory



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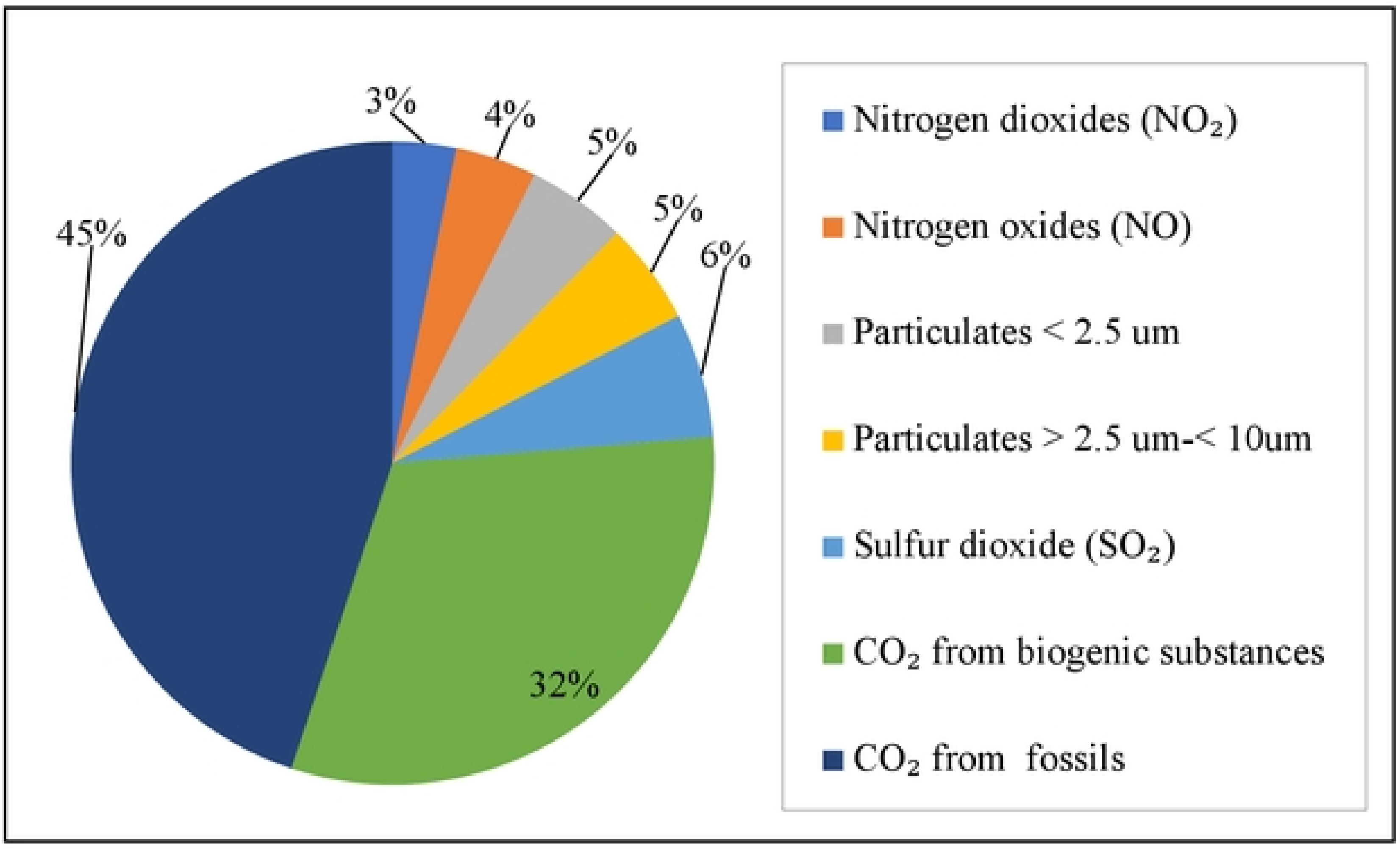

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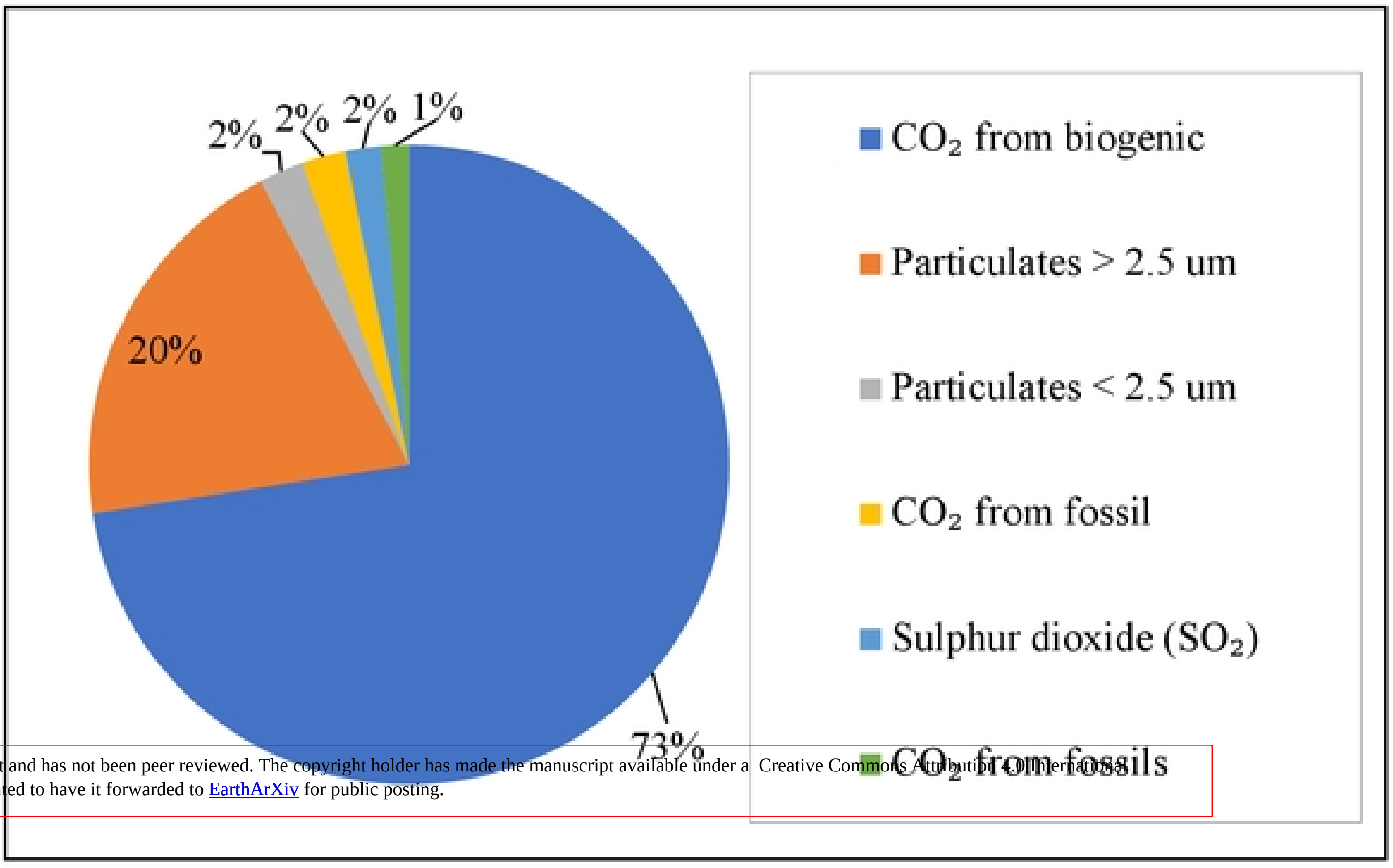

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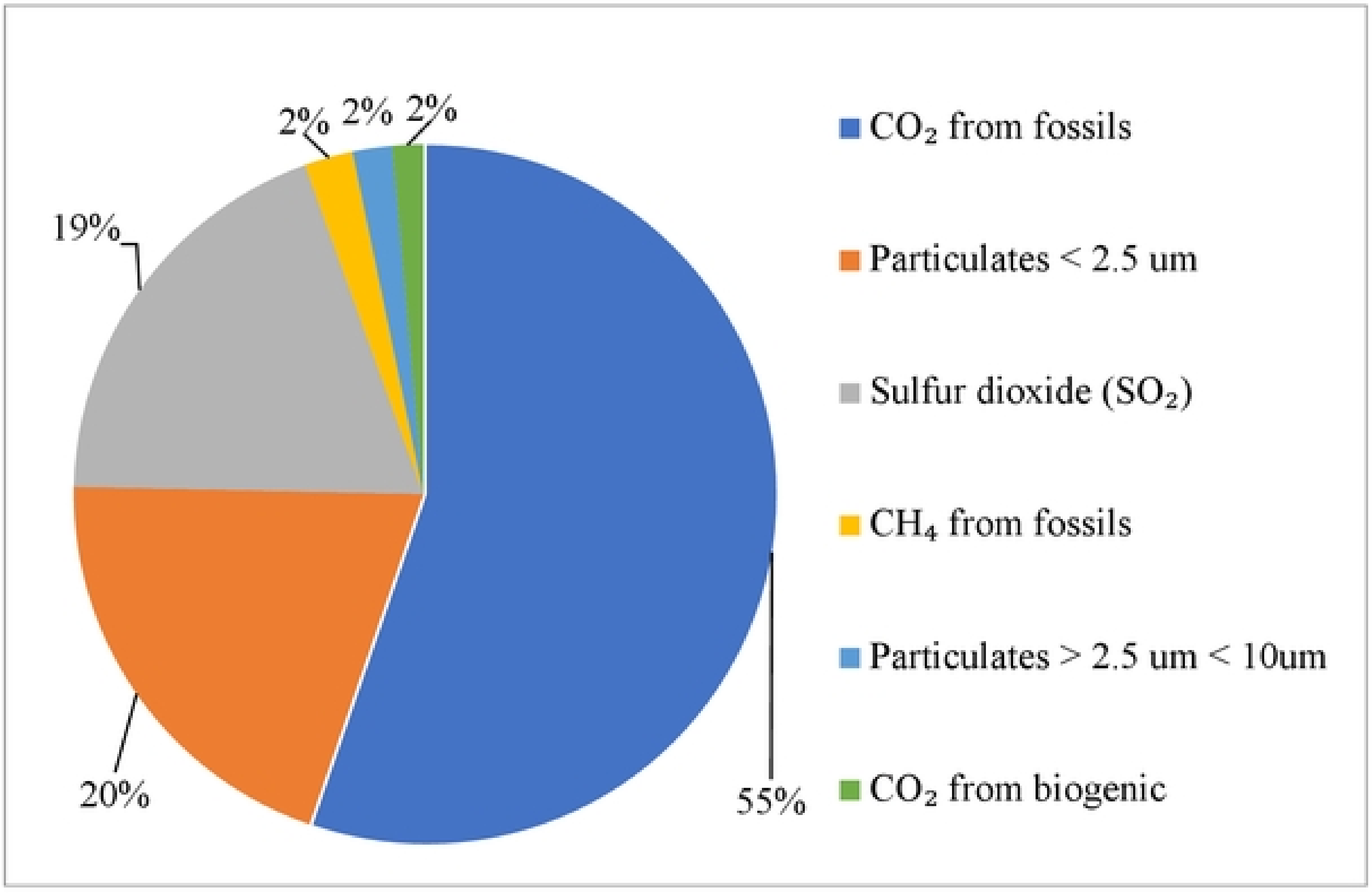

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