

**ANALYZING THE IMPACT OF BEVERAGES INDUSTRIES
ON THE AIR QUALITY AND CLIMATE CHANGE**



By

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**DEPARTMENT OF EARTH AND ENVIRONMENTAL
SCIENCES**

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ABSTRACT

The study evaluated the stack emissions and ambient air quality of five beverage industries across five cities in Pakistan. High volume air sampler, LANCOM gas analyzer and HORIBA AQMS were utilized to measure and assess key parameters in the ambient air and stack emissions from boilers and generators at the industries. The results of ambient air quality at five beverage industries revealed that all assessed parameters were within the recommended limit given Pak NEQs. Noise levels were high but within WHO guidelines. All five industries had different wind speed, direction, humidity, and temperature. Faisalabad's diesel-powered boilers and generators exceeded Pak NEQs in stack emissions, with boiler 1 emitting the maximum CO and SO₂, boiler 2, generator 2 and 3 generating NO, NO_x, and PM under stipulated load conditions. Boiler 1 in Lahore released more CO, NO, NO_x, and PM than Pak NEQs (natural gas boilers). NO₂ and SO₂ met Pak NEQs. Generators 1 and 3 exceeded Pak NEQ limits for CO, SO₂, NO, NO_x, and PM (diesel-fueled, fully loaded). Fully loaded natural gas boilers and diesel generators served Rawalpindi. SO₂ and NO₂ met Pak NEQs, but CO, NO, NO_x, and PM exceeded. Generators 2 and 3 released higher CO and NO_x. Diesel generators and natural gas boilers were completely loaded in Haripur. CO and NO₂ met Pak NEQs, whereas CO, SO₂, NO, NO_x, PM exceeded. Generators released the most CO and NO_x. NO was greater in boiler 1 (167 ± 23.06) $\mu\text{g}/\text{m}^3$ and generator 3 (190 ± 10.0) $\mu\text{g}/\text{m}^3$. Overall, emissions were minimal. Sheikhpura boiler 2 emitted more than boiler 1. CO (334.3 ± 30.2)%, SO₂, NO (423.0 ± 13.0) $\mu\text{g}/\text{m}^3$, NO_x (458.0 ± 18.0) $\mu\text{g}/\text{m}^3$, and PM (89.6 ± 0.1) $\mu\text{g}/\text{m}^3$ exceeded Pak NEQs. Diesel emissions peaked at generator 3. CO, SO₂, NO, NO_x, PM exceeded limits; NO₂ and CO₂ were within. Both machines were fully loaded. Comparative investigation showed that boiler 1 in Lahore was above the safe PM level (62.2 $\mu\text{g}/\text{m}^3$), while boiler 2 was below the 35 $\mu\text{g}/\text{m}^3$ limit. PM emissions from Sheikhpura boiler 2 were high (89.4 $\mu\text{g}/\text{m}^3$). Haripur and Rawalpindi boilers had tolerable PM levels. Inefficient fuel combustion, fuel quality, and pollution management can cause boiler PM. All beverage boilers exceeded Pak NEQs' CO limitations (232.6 $\mu\text{g}/\text{m}^3$). Improper fuel ratios and combustion temperatures increase CO emissions. Maintenance issues with furnaces and controls might increase emissions.

Boilers in Faisalabad have higher SO₂ levels (409.3 µg/m³). All boiler NO₂ emissions were fine. Generators disregarded Pak EPA PM Emission's regulations (76.8 µg/m³). Diesel combustion with low air-fuel mixing ratios creates particles. The NO₂ emissions were safe. SO₂ levels in Lahore, Sheikhupura, and Faisalabad (161.6 µg/m³) surpassed Pak NEQs due to diesel generators. Rawalpindi and Haripur had safe SO₂ levels. Additionally, generators surpassed CO (284.8 µg/m³) Pak NEQ emission limits. Poor diesel generator maintenance and control increase CO emissions. Faisalabad and Rawalpindi have the largest CO₂ equivalent emission potentials, followed by Lahore, Haripur, and Sheikhupura. Boilers have greater CO₂ percentages and equivalents than generators. CO₂ percentages range from 9.47% to 9.57%, or 0.17 kg/m³. The CO₂ Eq results of GWP showed that emission management and mitigation activities should target boilers and generators in facilities with greater emissions, improving efficiency, using cleaner fuels like natural gas, optimizing processes, and cleaner technology.

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ABBREVIATIONS

AAMS	Ambient Air Quality Monitoring System
CDP	Clean Development Project
CO	Carbon monoxide
FBT	Food, Beverages, and Tobacco
FSB	Faisalabad
GDP	Gross Domestic Product
GHGs	Greenhouse Gas Emissions
GWP	Global Warming Potential
HVAS	High Volume Air Sampler
IPCC	Intergovernmental Panel on Climate Change
KPK	Khyber Pakhtunkhwa
LHR	Lahore
NAAQs	National Ambient Air Quality Standards
NRE PERUse	Non-Renewable Energy, Product Environmental Responsible Usage (PERUse)
PAK NEQS	Pakistan National Environmental Quality Standards
PIM	Product Impact Minimization
PM	Particulate Matter
PPEs	Prioritized Policy Emissions
RWP	Rawalpindi
SCP	Sustainable Consumption and Production
WHO	World Health Consumption
WRI	Waste Reduction Initiatives (WRI) and Organic Product Initiatives

CHAPTER 1

INTRODUCTION

1.1 Ambient air quality

Human health is closely linked to environment. Clean air is a natural blessing and essential to human survival. Over the past 50 years, air pollution's effects on health and well-being have been studied extensively. Polluted air causes several ailments, including cardiovascular, respiratory, and lung cancer. Air pollution harms animals and plants (Almetwally et al., 2020). Ambient air quality is outside air, not indoor air. Ambient air quality is monitored to fulfill health and environmental norms. 78% nitrogen and 21% oxygen make up ambient air. It is natural and unpolluted by industrial fumes, automobile exhaust, and other contaminants (McClellan, 2002). The Clean Air Act mandates the EPA to establish National Ambient Air Quality Standards (NAAQS) for six "criteria pollutants," which are prevalent in outdoor air, detrimental to public health and the environment, and originate from many sources. The EPA states that primary standards safeguard human health with an adequate safety margin, whereas secondary standards protect public welfare from adverse impacts on soil, water, crops, plants, animals, weather, visibility, climate, and other factors (Esworthy, 2013). Specifying the measuring methods for assessing and achieving compliance is a crucial aspect of establishing a National Ambient Air Quality Standard. The samples collected for compliance are frequently utilized beyond their intended purpose to identify sources, assess the efficacy of controls, and ascertain the correlation between pollution levels and public health (Chow, 2015). The sharing of air quality information has been a prevalent policy instrument for emission reduction; yet, its effects on environmental and economic performance remain unclear (Deng et al., 2024). The WHO indicates that industries, households, automobiles, and trucks contribute to potentially hazardous ambient air pollution. Fine particulate matter constitutes the most detrimental pollutant. Combustion of fuel from vehicles, power generation facilities, industrial operations, residential heating, and biomass incineration generates the majority of fine particulate matter. The WHO reported that in 2019, 99% of the global population

resided in regions failing to meet its air quality guidelines, attributing 6.7 million premature deaths each year to ambient and household air pollution. The report estimated that outdoor air pollution resulted in 4.2 million premature fatalities globally in 2019 (WHO, 2019).

One of Pakistan's biggest environmental issues is air pollution, especially in major cities Lahore, Islamabad, and Karachi. It costs the GDP billions of rupees annually. Many factors, including atmospheric chemistry and motion and pollution emissions from natural and anthropogenic sources, affect ambient air quality (Asad et al., 2018). Air pollution is a major environmental issue in Pakistani cities and costs the government billions of rupees. Pollution costs the country rupees 62-65 billion yearly, or 1% of its GDP, according to a World Bank analysis. Vehicle emissions, fossil fuel burning, unleaded petrol, and power plants are primary causes of fine particle pollution. Transportation and industrialization worsen air quality more than other factors. A constantly growing population, industries, and cars are the main contributors of ambient air pollution today (Ishfaq and Ubaud 2005).

Over the past decade, Pakistan has experienced significant increases in population growth, urbanization, industrialization, motorization, and energy consumption. Consequently, there has been a significant increase in the variety and quantity of emission sources for different air pollutants. Nevertheless, the country's inadequate air quality management capacities are declining the air quality. Data from multiple governmental institutions and international entities has demonstrated that air pollution poses a substantial threat to the environment, quality of life, and public health (Colbeck et al. 2010). The Pakistan Environmental Protection Agency built the Central Laboratory for Environmental Analysis and Networking (CLEAN) in Islamabad. In 2000, the Pakistan Environmental Protection Agency (EPA) and JICA performed initial air pollution study in Lahore, Rawalpindi, and Islamabad. Mobile and permanent stations measured air pollutants hourly. CLEAN monitors Islamabad's air frequently. Efforts have been taken to improve the air quality in major cities of Pakistan (Asad et al., 2018).

1.1.1 Ambient air quality standards (AAQS)

Table 1.1: National and international standards for ambient air quality (AAQS)

Standards	Time Weighted Average	NO ₂ µg/m ³	SO ₂ µg/m ³	CO mg/m ³	O ₃ µg/m ³	PM 10 µg/m ³	PM 2.5 µg/m ³	Lead (Pb) µg/m ³
Pak NEQS	Annual* 24 hrs** 8 hrs** 1 hrs	40 80	80 120	5 10	130 180	120 150	≤ 15 ≤ 35 ≤ 15	1 1.5
USEPA	Annual* 24 hrs**	- 100	- 200	10 -	140 -	- 150	≤ 9 ≤ 35	0.15
WHO	Annual* 24 hrs**	10 25	20 40	10 -	≤ 100 -	≤ 15 ≤ 45	≤ 5 ≤ 15	-

*Annual arithmetic means of minimum 104 measurements in a year taken twice a week 24 hourly at uniform interval

**24 hourly/8 hourly values should be met 98% of the in a year; 2% of the time it may exceed, but not on two consecutive days.

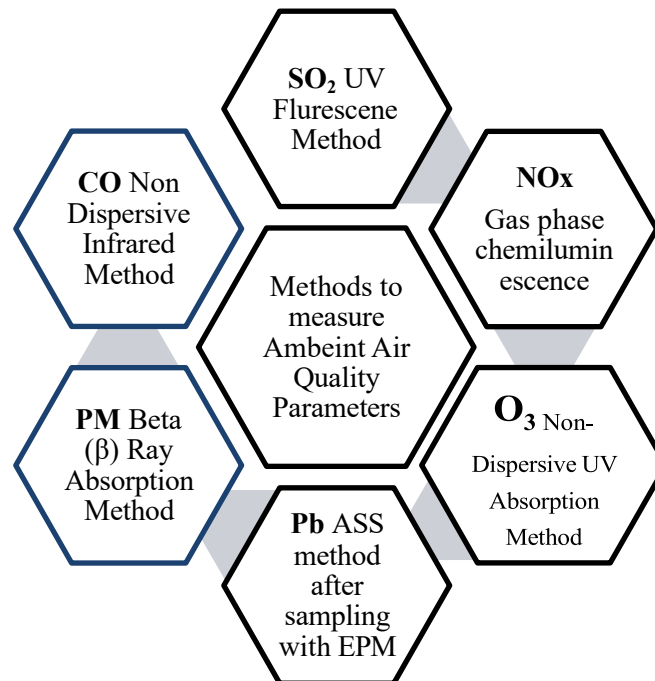


Figure 1.1: Methods of measurements for different air quality parameters

1.2 Air pollution and major air pollutants

Urban air quality is a complex combination of natural and manmade factors. Urban air pollution is a major environmental issue, especially in developing nations. Air contaminants are emitted and transmitted in urban areas, causing ambient air pollution. Motor traffic emissions are a major global source. Air contaminants diffuse, dilute, and photochemically react during transmission. Air pollution varies temporally and spatially (Raicu, and Stefan, 2015). Outdoor air pollution has thousands of components. Air pollutants are classified by source into primary and secondary categories. Air pollutants known as primary pollutants are directly emitted from sources such as industries and autos. CO, CO₂, CH₄, VOCs, NH₃, SO₂, and NO_x are examples. Secondary air pollutants are produced by chemical reactions in the atmosphere. Typical pollutants include PM, ozone, nitric acid, sulphate, and Sulphuric acid. PM and NO₂ are both main and secondary pollutants (Singh et al., 2025).

A health standpoint, airborne particle matter (PM) and gaseous pollutants ozone, nitrogen dioxide (NO₂), volatile organic compounds (including benzene), carbon monoxide (CO), and Sulphur dioxide (SO₂) are particularly important. Fossil fuel burning releases primary pollutants such soot and nitrogen and Sulphur oxides. Primary particles come from motorized road traffic, electricity generation, industry, and domestic heating. Ozone (O₃) and PM are the principal secondary pollutants created when primary pollutants react. Particles, whether primary or secondary, are classed as coarse (<10 µm; PM 10), fine (<2.5 µm; PM 2.5), or ultrafine (<0.1 µm; PM 0.1) based on size. The coarse particle fraction contains PM 2.5, which makes up 50% of PM 10 (Mannucci et al., 2017).

Airborne solid and liquid droplets are particulates. PM is solid particles formed by handling, crushing, grinding, and spraying. Burning coal in power and industrial sectors, petrol and diesel in cars, construction, and agriculture produces PM. Air pollution is a complex combination of microscopic and big particles with different origins and chemicals. Lead, asbestos, copper, and zinc are particulates. Particles can stay in the atmosphere for seconds to months depending on size, density, settling velocity, and turbulence. Industrial, agricultural, construction, plant pollen, road traffic, and other natural sources produce 2.5-100-micron smoke and dust. Particulates can impair vision,

change urban climate, and modify precipitation chemistry. Health consequences of particles vary by size (Doreswamy and Sudheendro, 2010).

Sulphur dioxide is produced when fossil fuels like coal and oil undergo oxidation during combustion. Sulphur dioxide causes air pollution and acidic deposition due to its extended lifetime and long-distance transport in the atmosphere. Sulphur dioxide, a colorless, smelly gas produced by coal burning, contains 10% to 15% Sulphur as impurities in coal. Nearly 75% of atmospheric SO_2 comes from fossil fuel burning in power plants and furnaces, while 25% comes from petroleum refineries and non-ferrous smelters. Sulphuric acid, formed from SO_2 and water, is a threat to life and materials. SO_2 constricts air airways, causing issues for asthmatics and small children. Even quick exposure to modest levels of SO_2 might cause respiratory difficulties (Emberson et al., 2001).

CO, a flammable gas, is toxic, colorless, and odorless. CO has a long-lasting presence in the atmosphere, lasting from 0.1 to 5 years, and reacts slowly with other chemicals. CO is a main pollutant produced by humans and contributes to ground-level ozone formation (Chen et al., 2007). Tissue damage, dizziness, disorientation, chest pain, and reduced eyesight result from CO replacing oxygen in red cells and limiting oxygen transport to important organs like the heart and brain. Extreme CO exposure can kill. Low ambient CO concentrations can damage the brain over time. For those with underlying health conditions, short-term CO exposure may trigger chest pain due to low blood oxygen (Yoo et al., 2015). Lead is abundant on Earth. Ores produce lead. Lead is primarily released into the atmosphere as a pollutant from vehicles utilizing lead-containing fuel. Lead compound is used in petrol as an anti-knocking agent. Lead inhalation reduces hemoglobin production, causing anemia. Other effects include liver and kidney infections in people (Petit et al., 2015).

Ozone is a highly reactive atmospheric gas having three oxygen atoms. It is colorless to pale blue. Ozone is stratospheric and tropospheric. Stratospheric ozone is good and ground-level ozone is bad. UV light is damaging to humans, but the stratospheric ozone layer absorbs it. Ground-level tropospheric O_3 reacts with other chemicals, hurting individuals and the environment (Fowler et al., 2018). Ground-level O_3 and PM contribute to haze. Long-range transfer is possible with O_3 , an air contaminant that lasts weeks. Ozone

is a respiratory irritant that affects mucous membranes, lung tissues, and respiratory functions. It affects lung mechanical function, causing chest tightness, coughing, wheezing, and lung function declines. The main cause of ozone-induced lung volume loss is inhalation capacity (Suh et al., 2000). Flora and ecosystem are affected by ground-level ozone, a powerful oxidizer. This damages horticultural crops, reducing production and costing farmers financially. Cell injury and tissue death can result from reddening and necrosis in local crops. Ground-level O₃ reduces photosynthesis, inhibits crop growth, and ages leaves, reducing agricultural productivity (Sicard, 2021).

After burning fossil fuels like coal and oil, nitrogen in the air is oxidized to nitric oxide (NO) and then to nitrogen dioxide (NO₂). Nitrogen oxides are nitric oxide and nitrogen dioxides together. Oxides of nitrogen contain toxic gases and contribute to photochemical air pollution (Zhang et al., 2021). Airborne chemical processes convert NO_x to nitrate aerosols. Nitrate aerosol absorbs water and scatters light, making the sky cloudy. Photochemical smog from NO_x, VOC, and sunlight harms humans. Airborne NO_x quickly combines with water to generate nitric acid. Nitric acid mixed with water and snow forms acid rain ((Streets, and Waldhoff, 2000).

1.2.1 Possible Sources

Air pollution in Pakistan originates from numerous sources, including transportation, power plants, industrial processes, garbage incineration, and construction activities. The food and beverage sectors emit pollutants via fuel burning in boilers, generators, and processing equipment. These emissions encompass CO₂, NO_x, SO₂, and PM, resulting in deteriorated air quality and contributing to climate change. This particular industry, often neglected, is emerging as a significant source of localized air pollution, highlighting the necessity for enhanced emission control and environmental legislation (Akhtar et al., 2017; Bhatti and Fazal 2020).

The principal sources of NO₂ include gas stoves and pilot lights (natural gas and propane), wood stoves and fireplaces, gas- and kerosene-fueled space heaters, gasoline engines and outdoor air (Alberts, 2015). PM is both natural and manmade. Dust from highways, construction sites, wildfires, sea spray, and volcanoes is the main source of PM.

Released directly into the atmosphere. NH_3 , SO_x , NO_x , and VOCs are needed to make secondary PM. Chemical processes produce secondary particles from precursors. Industries (combustion), transportation (automobiles, aircraft, ships), households (heating, cooking, personal care, cleaning), and agriculture (nitrogen fertilizer, animal manure) emit these. Secondary particle matter requires more steps to reduce precursor levels than main particle matter, making control harder. CO is thus generated by vehicle exhaust, small engine devices like lawnmowers, and heating systems such as fireplaces, oil burners, and fire. CO emissions come mostly from road traffic. High-temperature cooking and fuel burning at home/building generates CO. Road traffic and domestic oil and gas heating and cooking appliances emit NO_x . Additionally, agricultural soils that employ a lot of N fertilizer generate a lot of NO_x . SO_x are released from the combustion of home fuels used for heating and cooking, as these fuels typically include Sulphur. Industrial activity causes four main air pollutants, carbon monoxide, oxides of Sulphur, oxides of nitrogen, and dust from combustion; photochemical oxidants, carbon monoxide, and Sulphuric acid fumes from stationary processes, such as furnaces, refineries, etc.; toxic organic gases from hazardous waste processing; and hydrocarbons, oxides of nitrogen, carbon monoxide, and particulate from mobile processes (Wei and Wang, 2021).

The industrial sector is Pakistan's second largest, accounting for 19% of GDP. Recently, local and global factors have driven its growth. In 1995, the Pakistan Bureau of Statistics counted 4474 LSMI (Bhatti and Fazal 2020). The number exploded to 42,578 in 2015–2016 from 8680 in 2005–2006. Pakistani industry grows with globalization and personal remittances. Industry is a major source of air pollution in Pakistan. According to research, industrial SO_2 emissions grew 52 times between 1977 and 1998 (Ajmair and Hussain, 2017).

Industrialization has also resulted in an increasing demand for energy, much of which has historically been sourced from fossil fuels like coal, oil, and natural gas. These energy sources are major contributors to air pollution, releasing harmful gases and particulate matter into the atmosphere (Yu et al., 2023). In addition to power generation, industrial processes such as mining, manufacturing, and chemical production are significant sources of air pollution. Nitrogen oxides contribute to smog formation and are

a precursor to ozone, which can irritate the respiratory system. Volatile organic compounds (VOCs): A group of chemicals released by industrial solvents, paints, and fuels that can contribute to the formation of ground-level ozone and smog (Wu et al., 2023).

1.2.2 Health impacts

Air pollution and stack emissions causes and worsens several respiratory disorders as asthma, COPD, and lung cancer (Jiang et al., 2016). Hong Kong and Taipei studies found that ambient O₃, NO₂, PM_{2.5}, and SO₂ levels increased asthma and pneumonia hospital admissions. A comprehensive study found that indoor air pollution from solid fuel combustion was a risk factor for COPD in low-income adults, particularly non-smoking women (Qiu et al., 2014). Many studies have linked air pollution to lung cancer, with women having the highest risk due to their higher indoor air pollution exposure (Guo et al., 2017). The contribution of industrialization to air pollution has a direct effect on human health. Industrial pollutants such as particulate matter, Sulphur dioxide, and nitrogen oxides can lead to several health complications, including asthma, bronchitis, lung cancer, cardiovascular disease, and premature death (Jensen, 2024). NO_x to nitrate conversion causes eutrophication. Nutrient excess causes plant and algae blossoming, hypoxia, and marine organism issues. NO₂ increases respiratory problems. NO₂ in the lungs produces inflammation and decreases immunity, causing bronchitis, coughing, flu, and cold. Asthma and COPD patients can die from NO₂ attacks. In children who breathe faster per unit of body weight than adults, prolonged NO₂ exposure can cause asthma. Children with long-term NO₂ exposure may have smaller lungs at maturity, according to other studies (Streets, and Waldhoff, 2000)

Short-term or long-term air pollution exposure might cause health problems. Acute effects include upper respiratory tract irritation and asthma symptoms after short-term exposure. Long-term exposure causes cardiovascular disorders, reproductive problems and genotoxicity (Zhang et al., 2018). Children are more susceptible to ambient air pollution because their defense mechanisms are still developing and they inhale more air per body weight than adults. Mothers exposed to high air pollution during pregnancy can harm their fetuses. Ambient air pollution increases respiratory newborn mortality (Bertazzi, 2013). Fine particles can aggravate asthma, increase allergen sensitization, and reduce lung

function. Oxidant air pollution appears to harm lung growth in youngsters. Air pollutants cause oxidative stress, and preliminary research suggest antioxidant supplementation may protect against it (Salvi, 2007). In developing countries, population expansion, industrialization, and urbanization have created congested urban centers with poor air quality, making acute and long-term exposure to ambient air pollution even more dangerous. In developing nations with large economic and social disparities, biomass fuels (coal, wood, and other solid fuels) can produce substantial indoor air pollution, especially in rural areas. Over three billion people, especially in underdeveloped countries, use biomass for home energy (Pena and Rollins, 2017).

Global air pollution inhibits economic growth, worsens poverty and inequality, endangers health, and contributes to climate change. Due to decreased atmospheric diffusion and air pollution accumulation, highly populated urban regions often have this issue. Economic, social, and environmental changes caused by industrialization-based urbanization make areas more sensitive to environmental contamination, notably air pollution (Thanvisitthpon et al., 2024). Industrial air pollution affects agricultural development and yield, according to many research. Environmental factors, notably air quality, affect crop productivity. Air pollution lowers crop output. In 1997, air pollution cost the US \$40–50 billion. In Pakistan, the 2003–2004 season saw a 43%, 39%, and 18% decrease in rice yields for three varieties when the seasonal average concentrations of O₃, NO₂, and SO₂ were 70 ppb, 28 ppb, and 15 ppb, respectively (Lee, 2023; Wahid, 2006).

1.3 Beverage Industries

Food processing is crucial since population growth drives demand for food. Production processes in food processing are shifting from traditional to high-value products. Food processing, despite its benefits, is a major polluter of the environment due to its heavy use of energy and water resources (Alsaffar, 2016). One major Greenhouse gases (GHG) emitter is the food and beverage industry. Food production emits 25% of global anthropogenic GHGs, and a third of global emissions. Significant worldwide GHG emission reductions require food and beverage industry reductions. Food and beverage industries' distribution networks emit most of their emissions, thus adopting climate objectives to reduce them is crucial (Kobayashi and Richards, 2021). All sectors of the

economy must reduce greenhouse gas (GHG) emissions to combat climate change. Food production accounts for 34% of annual anthropogenic GHG emissions (Crippa et al., 2021).

Food and beverage industries contribute to one-third of global anthropogenic greenhouse gas emissions, and population expansion will elevate both food consumption and greenhouse gas emissions. The food and beverage sectors, as significant polluters, must quantify their emissions to establish climate objectives. All emissions across the value chain must be accounted for in emission targets. Numerous studies examine climate objectives or emissions reporting from major industries across various sectors although few focus on food and beverage industries (Searchinger et al., 2019).

Within the food and beverage sector, the branches with the highest turnover are Meat (20%), Beverage, which consists of beer, juice, soft drinks, and wine production (15%), Dairy (14%), Bakery (11%), and Processed F&V (Fruits and Vegetables) (6%). The Beverage branch, and more specifically beer production, is dominated by small and medium industries (70%), employing nearly 2 million people (direct and indirect) while generating over 50 billion dollars in added value. Since growing regulations and legal requirements need lower energy usage and carbon emissions, food and beverage manufacturers should constantly monitor their energy (fuel and electricity) consumption. Energy utilization affects product cost, although as less than 5% of production cost, it is less important (Gallego-Alvarez et al., 2025). Beer ranks fifth in global consumption. Beer makes up over three-quarters of global alcohol consumption and was produced at 1.96 billion hectolitres (hL). Due to resource utilization, large-scale beer production has had major environmental implications. Alcoholic beverages, including beer, contribute 0.7% of global GHG emissions over their entire lifecycle (Gomez et al., 2016).

Pakistan food and beverage industry is considered to be the largest industry with an export potential of 2% of total exports. Pakistan food and beverages industry is involved in various productions such as: Bakery items, different kind of sweets, dry vermicelli and chicken meat items (Shah et al., 2019). The beverage industries significantly contribute to the national economy but also plays a key role in greenhouse gases emissions and increasing carbon footprint. Although processed food has benefits, it uses significant energy and water resources and pollutes the environment through waste, air, noise

pollution and emissions as well. Additionally, inefficient production and consumption habits cause environmental contamination from food processing losses, wastes, and packaging materials (Amir et al., 2018).

Stack emissions from beverage manufacturing facilities discharge several pollutants and harmful gases, including carbon dioxide, nitrogen oxide, Sulphur dioxide, particulate matter, and volatile organic compounds, straight into the environment. These pollutants significantly contribute to air pollution, resulting in numerous respiratory issues, cardiovascular disorders, and deteriorating air quality (Hansen et al., 2022). These gases also exacerbate the greenhouse effect, further contributing to climate change and global warming. In proximity to such companies, acid rain may develop due to the accumulation of pollutants in the atmosphere, leading to soil acidification, which results in diminished soil quality and the loss of flora. Furthermore, heat emitted by stacks can elevate the total temperature, exacerbating urban heat island effects and intensifying temperature extremes. In Pakistan, where environmental regulations and compliance are seldom observed and rarely enforced, these impacts can pose long-term health concerns to public health and ecosystems (Meyer et al., 2016).

1.3.1 Beverage industry emissions

Industrial, electricity, and other combustion activities produce flue gas emissions from exhaust stacks or chimneys. Air pollution is caused by emissions of hazardous pollutants as PM, SO₂, NO_x, CO, VOCs, and CO₂. Due to their significance in respiratory ailments, climate change, and ecological damage, stack emissions are a major environmental and public health concern (Clairand et al., 2020). Boilers, steamers, hot water generation units used in beverage industries all contribute to stack emissions. All the engines (Automotive, diesel, and natural gas engines) including alternative energy sources such as generators also contribute to net emissions. Flares related to off-gassing from fermentation tanks, vaporizer blender systems, and wastewater treatment also contribute and fulfill their function. Incinerators are employed to combust diverse materials and diminish waste volume. All heaters, dryers and cooling/refrigeration/cold storage equipment used for in-plant processing, sanitation, and employee comfort (Routable, 2010). Company cars, employee vehicles, sales and merchandising vehicles, rail engines,

and trucks are used for corporate industrial travel. This also includes operational control of waste treatment contributing to carbon footprint and emissions (Chastain et al., 2009). Due to the enormous networks needed to distribute goods, transport accounts for 13% of GHG emissions. Directly purchased energy, steam, chilled water, refrigeration, evaporators, dryers, and compressed air emissions at company-owned or controlled facilities. Indirect utility emissions at regulated facilities, including energy used to operate leased buildings and associated activities, are also considered (Hansen et al., 2022). 35% of GHG emissions come from beverage raw material production and pre-processing. Table 1.2 summarizes the raw materials used in beverage industries and resulting emissions.

Table 1.2: Raw materials used in beverage industries and contribution to stack emissions

Raw materials	Use in Beverage Industry	Associated Emissions
Water	Base ingredient	Use in boilers can lead to fuel emissions
Sugar/Syrup	Sweeteners in drinks and juices	Processing requires heat which can release NO _x , Sox, CO ₂ from boilers or fuel combustion
Grains (Corn, Barley)	Brewing or fermentation in beer and spirit	Fermentation releases CO ₂ and drying them releases combustion emissions
Fruits/Vegetables	Juices, concentrates, flavors	Peeling, drying, heating releases fuel combustion emissions
Carbon dioxide	Carbonation of soft drinks and beer	Loss from storage, possible fugitive emissions
Packaging material (Glass, Plastic, Cans)	Bottling, labeling, storage	Manufacturing or sterilizing packaging, emissions from energy use

Drinking packaging material affects carbon footprints, according to studies. Glass bottles have the biggest footprint at 675 g CO₂e/l, followed by aluminum and PET plastic at 190 and 245 g, respectively. Manufacturing these materials accounts for 23% of industry emissions. Building energy usage and equipment maintenance account for 11% of GHG emissions (Liu et al., 2023). The Figure 1.2 shows the share of emissions in percentages coming from beverage industry. Scope 1 emissions are direct emissions from owned or controlled sources, Scope 2 are indirect emissions from purchased energy, and Scope 3 covers all other indirect emissions, often from the value chain.

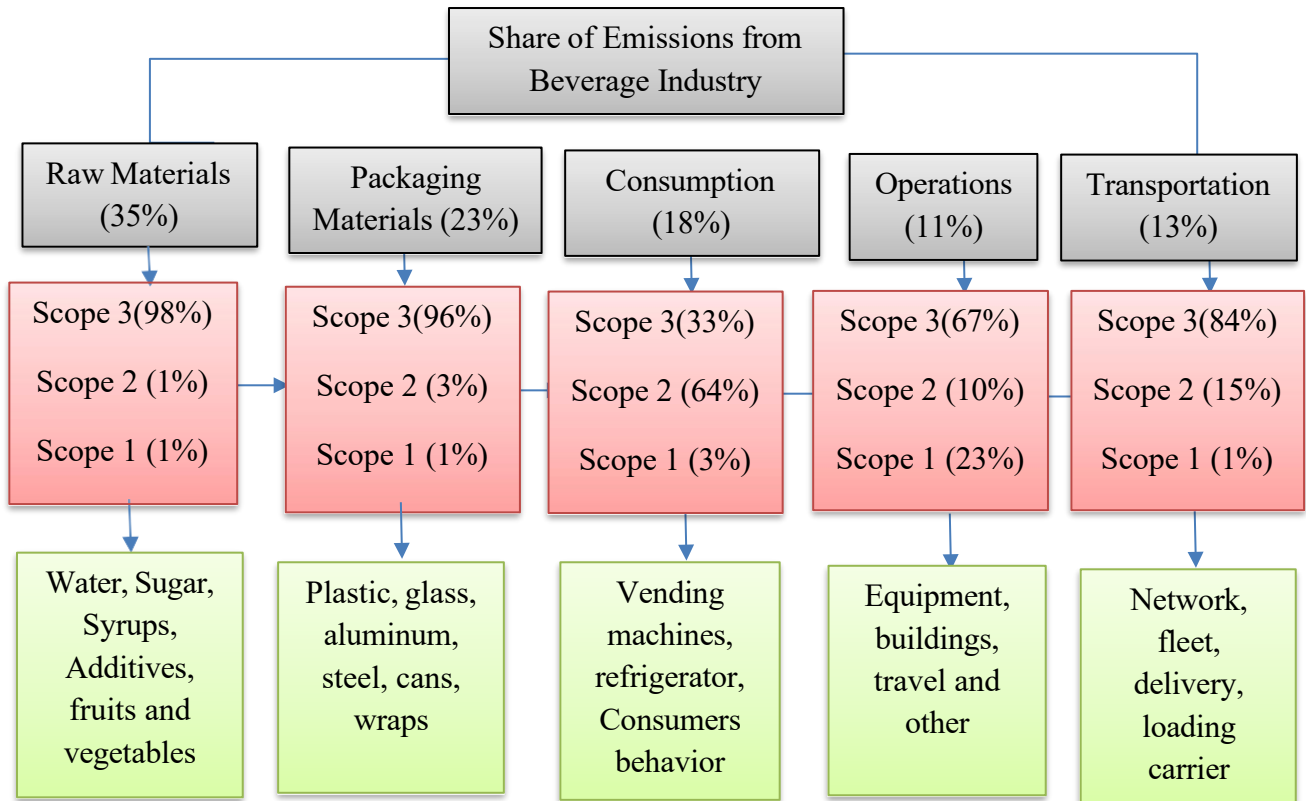


Figure 1.2: Flow sheet diagram illustrating shares of emissions from beverage industries

1.3.2 Monitoring

It is essential to mitigate and regulate stack emissions and any other emissions originating from industry that contribute to air pollution, climate change, and global warming. The concept was established within the framework of the Kyoto Protocol to establish a uniform methodology for assessing and contrasting the impacts of various gases

On global warming over a designated timeframe, usually 100 years (Naresh and Chakabarti, (2018). Global warming potential denotes the quantity of heat retained by a specific mass of a greenhouse gas in the atmosphere over a designated time frame, typically 100 years, in relation to the heat retained by an equivalent mass of carbon dioxide. This idea was created by the Intergovernmental Panel on Climate Change (IPCC) to offer a standardized method for evaluating the impact of various gases on global warming, and it is currently extensively utilized in climate policy and environmental science (Al-Yasiri and Géczi, 2021).

To lessen and monitor stack emissions in beverage industries it is important to implement reliable monitoring systems such as continuous emission monitoring systems (CEMs) which record and track real time levels of CO₂, NO_x, SO₂ and particulate matter. First the source should be identified and then corrective measure or steps can be taken such as switching to cleaner fuels, natural gas or bio fuels, adopting energy efficient boilers and installing air pollution control equipment such as electrostatic precipitators, fabric filters, and wet scrubbers etc. Additionally, maintaining the production processes, recycling heat, and reducing overall energy usage through automation and maintenance reducing further emissions. These actions can help reduce carbon footprint and may also play a key role in mitigating the global warming potential (GWP) associated with the industry operations (Akhtar et al., 2017).

1.4 Literature Review

Urban air pollution was a pressing environmental challenge that significantly impacted public health and ecosystem integrity. Noah, (2024) investigated sustainable mitigation strategies for urban air pollution, focusing on the life cycle assessment (LCA) of emissions and environmental impacts associated with beer production. Beer brewing was a complex process that involved raw material cultivation, transportation, production, packaging, and distribution, all contributing to the overall emissions profile. Furthermore, transportation and packaging choices had significantly influenced the overall emissions. Implementing those strategies significantly reduced the air quality impacts of beer production while fostering a more sustainable urban environment (Noah, 2024)

Calculating the environmental footprint required beverage companies to incorporate sustainability into their differentiation strategy. Detailed footprint estimation parameters were discussed by Jornet-Martínez et al. (2019). Water, air, and solid waste contamination were the key problems. Pesticides, complex oils, alkaline or acidic compounds, and other organic molecules were present in agro-industrial effluents. Air emissions included particulate matter, SO₂, NO_x, hydrocarbons, and organic chemicals. Presented the state of in situ analytical equipment for this purpose. The MINTOTA Group's CALIFICAMET tool compared devices. The tool evaluated merit (quantified from 1 to 5 according to their adequacy to the estimation of the desired parameter), sustainability (from the calculation of their carbon footprint and generated residues, quantified from 1 to 5 according to quantity, type, and recycling possibilities), chemical and health risk (quantified 1–5 according to hazard and toxicity), and cost (Jornet-Martínez et al., 2019).

Hansen et al. (2022) explored the state and quality of corporate emissions reporting and target setting in the food chain by surveying the major 50 food and beverage manufacturers' 2018 CDP public emission reports. Every year, 7 companies failed to submit emissions, and many others provided insufficient figures. Only 10% of corporations had expressly covered land-use change emissions, which were crucial to the food system. More than a third of Scope 3 emissions went unaddressed by company emissions reduction targets. Our findings, along with the relatively poor reporting of Scope 3 emissions, suggested that the food and beverage industry had to urgently enhance GHG emissions reporting and management to mitigate climate change. Sector-specific guidance for Scope 3 that prioritized the most important aspects was needed for food system enterprises to report emissions more accurately. Three categories, including a land-use change category, were presented along with simple, easy-to-apply techniques to calculate emissions from these high-priority areas (Hansen et al., 2022).

Fifteen percent of global GHG emissions came from agriculture, and companies in the food and beverage industry began to set climate goals. Reavis et al. (2022) examined the GHG emissions reporting practices and climate goals of the top 100 global food and beverage companies (as ranked by Food Engineering) and determined whether their goals aligned with the science of keeping climate warming well below a 2°C increase. Our results

presented the disclosure and emission goals of the top 100 global food and beverage companies and highlighted an urgent need to have begun and continued to set truly ambitious, science-aligned climate goals (Reavis et al., 2022).

Meyers et al. (2016) conducted basic and extensive audits of small and medium-sized food and beverage companies in six EU nations and assessed product-specific energy use and identified energy and carbon emission reduction measures. These approaches led to energy savings of up to 45% and carbon reductions of up to 30% (~30,000 t CO₂ equivalent in certified enterprises), varying by company type, size, and fuel choice. Small enterprises and coal-using companies had the most room for improvement, but it varied by product and heating and cooling equipment. Companies found expenses too high, lacked knowledge of efficient technology and their performance, or lacked managerial support to implement efficiency measures (Meyers et al., 2016).

Gallego-Alvarez et al. (2025) examined food and beverage firms' environmental reporting procedures across countries and continents. Multivariate approaches were used to analyze the joint behavior of numerous variables and provide insight into how countries and continents performed in environmental indicators. Logistic biplot showed a considerable increase in the 19 environmental variables associated to resource usage during the entire period, along with changes in priority. As with resource consumption, emissions grew with time and enterprises in this sector prioritized policy emissions (PE), waste reduction initiatives (WRI), and target emissions. The business priorities in innovation were product impact minimization (PIM), organic product initiatives (OPI), product environmental responsible usage (PERUse), and environmental products (Gallego-Alvarez et al., 2025).

Roundtable, (2010) investigated the role of food, beverages, and tobacco in contributing and mitigating CO₂ emissions in the top industrial countries. Economic growth and renewable and non-renewable energy consumption were integrated as control variables in the empirical model. Additionally, the results indicated that renewable energy (RE) consumption contributed to reducing emissions, while non-renewable energy (NRE) and food, beverages, and tobacco (FBT) led to an increase in emissions levels in the long run. The study demonstrated a bidirectional long-run relationship between CO₂ emissions,

non-renewable energy, and economic growth. Moreover, no causality between food, beverages, and tobacco and any other variable was recorded.

Climate change is a primary and formidable challenge for developing economies such as Pakistan. Akhtar et al. (2017) concentrated on quantifying the carbon footprint of a beverage bottling facility and monitoring significant greenhouse gases, so elucidating the facility's contribution to greenhouse gas emissions as an initial step in addressing climate change. The methodological approach was based on the GHG Protocol and IPCC recommendations. The timeframe from March 2015 to March 2016 functioned as the reference year for computations. The industry's total carbon footprint was 29,880.26177 tCO₂e. The most CO₂ emissions originated from indirect sources, as determined by GHG Protocol and IPCC criteria. This study allowed industries to quantify their carbon footprint, so equipping the government with a strategy to address climate change (Akhtar et al., 2017).

Intense energy, food, and water consumption exhausted resources. Pakistan faces significant challenges regarding sustainable consumption and production (SCP). Food is crucial for socioeconomic development in an agrarian economy. Asian nations surpassed Pakistan in resource efficiency. Environmental Management Systems were crucial for organizational sustainability. Food manufacturing generates solid waste, water waste, air pollution, noise, odor, and excessive use of energy and water, as indicated by prior research. SCP technology reduced waste and promoted secure, sustainable human habitats. Shah et al. (2019) conducted semi-structured interviews with owners and managers of food and beverage processing enterprises in Pakistan. Purposive and snowball sampling analyzed environmental management techniques, challenges, and incentives for EMS implementation. The primary hurdles included insufficient knowledge, inadequate environmental rules, high certification costs, complex documentation, and limited access to new technologies (Shah et al., 2019).

A growing number of companies in the brewery industry committed to measuring and reducing their greenhouse gas (GHG) emissions. “Shin and Searcy (2018), investigated the challenges and benefits associated with measuring and reducing GHG emissions in the craft brewery industry. The research took place in Ontario, Canada, which experienced

strong growth in the craft brewery industry. A case study and semi-structured interviews among Ontario Craft Brewers were carried out. The case study indicated that indirect (scope 3 GHGs under the WBCSD & WRI GHG Protocol) GHG sources accounted for 46. The case study utilized primary data from the case company and secondary data, including emission factors obtained from external sources. The case study and interviews revealed that the main challenges in calculating brewery GHGs were secondary data availability, technical knowledge, and finances (Shin, and Searcy, 2018).

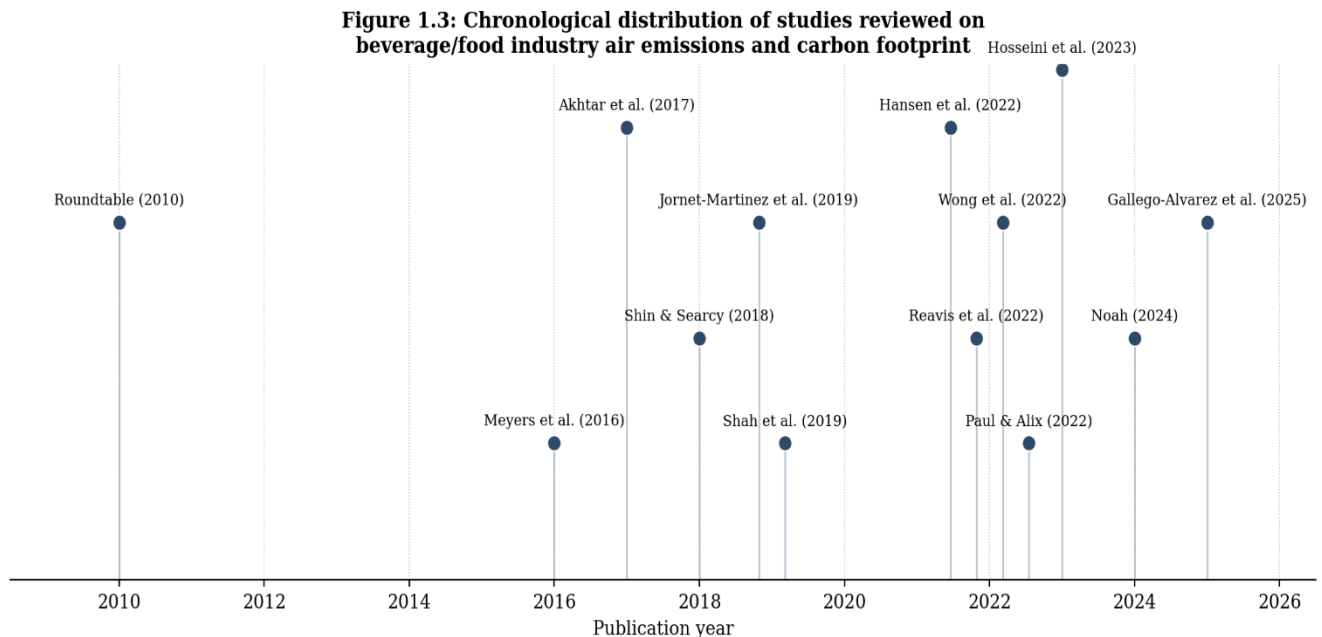


Figure 3.3 Chronological Distribution of Studies reviewed on Beverages / food Industry Air Emission and Carbon Footprint

The global rise in beverage consumption caused massive energy and carbon emissions throughout product life cycles. For complicated supply chain products and services, a new input-process-output product carbon footprint (PCF) model was created. Wong et al. (2022) analyzed a carbonated drink product's PCF at each significant life cycle step and compared to GHG Protocol methods. Cradle-to-grave analysis showed that retail and distribution led product life cycle emissions. A retail distribution routing optimization model and retail vending equipment analysis explored energy and carbon footprint reduction options. Future sustainable development of PCF of similar beverage items from

various nations and mitigation techniques using dynamic routing distribution were studied (Wong et al., 2022).

At ZamZam, a beverage company, a 95%-efficient absorption-refrigeration machine captured CO₂ from diesel-fired boiler flue gas before it created this CO₂ capture and utilization (CCU) approach. ReCiPe, cumulative energy demand, and AWARE impact assessment methodologies were used to evaluate the life-cycle economic, energy, and environmental consequences of CCU-routed electricity, liquid CO₂, and carbonated water supply chains. Hosseini et al. (2023) indicated that the CCU approach significantly enhanced liquid CO₂ supply for the sustainability of carbonated water manufacturing. CCU reduced the average economic, energy, and environmental consequences of liquid CO₂ supply by 55, 44, and 62% compared to on-site production. Only 10 carbonated-water production values were reduced. In contrast, the CCU pathway increased most energy generation environmental impacts. 22% was achieved while raising average toxicity- and eutrophication-related consequences by 55 and 30%, respectively, and production costs by 8% (Hosseini et al., 2023).

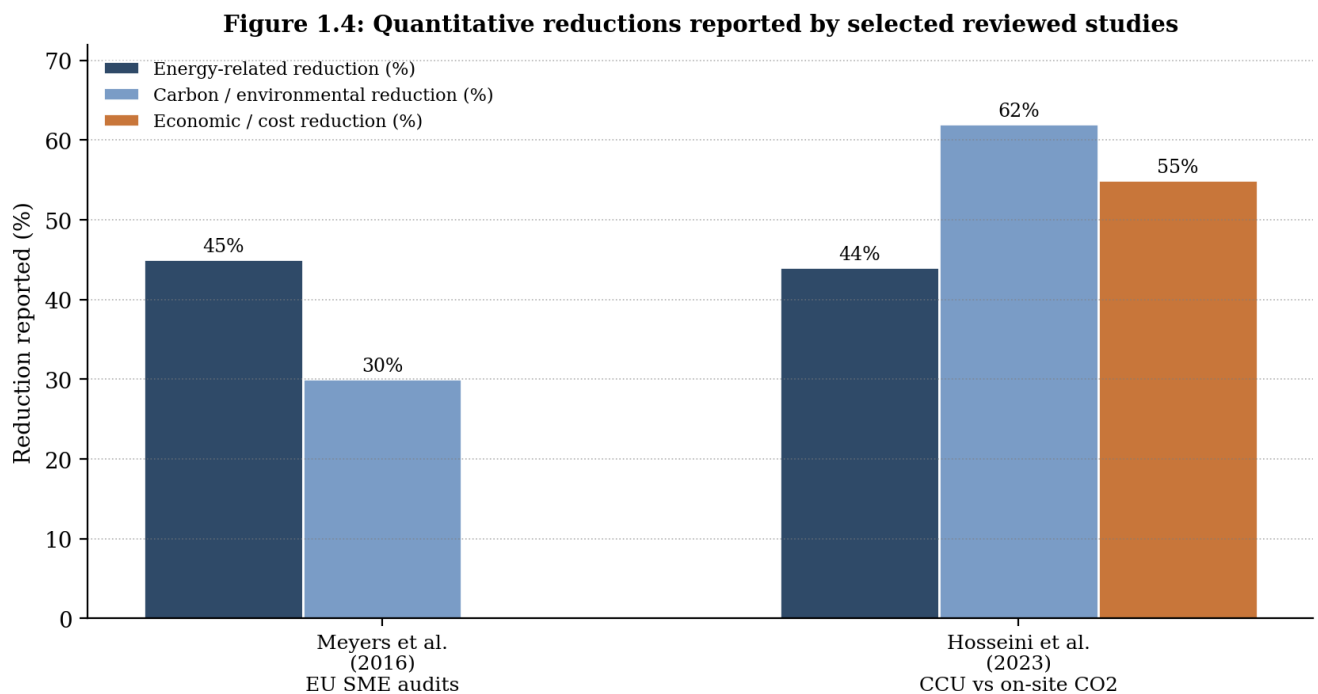


Figure 4.4 Quantitative reductions reported by selected reviewed studies

Approximately a third of all anthropogenic emissions come from the food and beverage sector, including pre- and post-production activities. In 2016, agriculture alone provided over 18% of world emissions. Paul and Alix, 2022 presented the CIA (Carbon Impact Analytics) campaign results, assessing 95 food and beverage firms' carbon performance and climate transition risk. These companies account for about 2,000 billion euros in market capitalization, or half of the sector's total (Paul and Alix, 2022).

The CIA campaign identified the following sector and stakeholder issues; energy consumption emissions contribute minimally to the sector's total emissions. Rather, emissions from agricultural practices, such as land usage and deforestation, are crucial. Few corporations specialize in producing and marketing high-carbon food products like meat, coffee, and chocolate. To adapt to the agricultural transformation, corporations must adjust their food products and agricultural techniques for raw input production. Few firms prioritize both components in their long-term strategy. Food and beverage companies lack transparency and consistency in reporting Scope 3 emissions, despite being their primary emission scope. Additional methodological improvements may be required to incorporate nutritional quality into the CIA evaluation approach for food and beverages. Enhanced reporting transparency by analyzed companies on product volumes and types might benefit this (Paul and Alix, 2022).

1.5 Problem Statement

The food and beverage industry has a large environmental impact due to its supply chains, energy use, cross-border operations, and waste generation (Asif, 2023). The present study evaluates stack emissions and potential contributions to global warming within the beverage industry. The rapid growth of the beverage industry in Pakistan has raised concerns regarding ambient air quality, stack emissions, and global warming (Akhtar et al., 2017). Comparative data among beverage facilities are limited to evaluate pollution and climate impacts. This gap hinders regulation and mitigation efforts. To ensure sustainability and facilitate informed decision-making, it is imperative to evaluate and analyze the air pollutants and greenhouse gas emissions of the beverage industry.

1.6 Research Objectives

The present study aims to achieve the following objectives:

1. To assess and quantify ambient air quality and characterize pollutant concentrations at five selected beverage production facilities.
2. To conduct a comparison of ambient air quality, stack emissions and Global Warming Potential (GWP) across the five beverage industries.

CHAPTER 2

METHODOLOGY

2.1 Study Area description

The study area consists of five beverage industries selected in five different cities of Pakistan based on the intended objectives of the present research. The five selected industries were located in cities namely, Rawalpindi, Lahore, Haripur, Sheikhupura, and Faisalabad.

Rawalpindi is Pakistan's fourth-largest metropolis. It symbolizes the rise of unplanned urbanization. Rawalpindi, a city of Punjab province in Pakistan, is situated on Potohar plateau at 33.6000° N latitude and 73.0667°E longitude (Bokhari et al., 2018). As to the Köppen-Geiger climate classification system, the city's climate is classified as humid and subtropical. The average annual temperature is 21.3 °C, and the average rainfall is 1255 mm. Rawalpindi is renowned for its considerable history, culture, and university both academically and research-wise. The topography of the city consists rolling hills, plains and valleys, the average elevation of the city being about 500 meters (1,600 ft) above sea level (Kamran et al., 2023; Kamran et al., 2024).

Haripur District, 610m above sea level in Khyber Pakhtunkhwa, Pakistan, situated at 33° 44'-34° 22' N latitude and 72°-35'-73°-15' E longitude. The district has 44 Union Councils and three sub-districts (Haripur, Khanpur, and Ghazi) on 1725 km². Haripur borders Abbottabad, Mansehra, Attock, Torghar, Swabi, Buner, Rawalpindi, and Islamabad. The district's 2017 NIPS population estimate was 1,003,031 and 580 people per square kilometers. Awan dominates the district, followed by Gujjar and Tanoli. Most of Haripur is rural, with about 12% living in cities. Temperatures range from 39°C in summer to 10°C in winter. Agriculture supports rural study area residents. Pastures, agricultural diversity, fodder agriculture, medicinal plant development, and livestock diversification drive economic growth (Siddique et al., 2021).

Sheikhupura, a famous Punjabi district, borders Lahore and Hafizabad. It is situated at 31°42'47" N and 73°58'41" E, with an elevation of 685 feet above sea level. Historical sites, industrial and agricultural areas, and high-quality rice make Sheikhupura notable. Sheikhupura borders Gujranwala, Hafizabad, Narowal, Nankana Sahib, and Lahore. District Sheikhupura is 3,280 km². Sheikhupura's population grew by 6.5 million in 50 years from 22,300 in 1951. This progress is due to agricultural and industrial operations in recent decades. Sheikhupura's population is rising and is 4,049,418 according to 2023 consensus (Raza et al., 2016).

With 11 million residents, Lahore is Pakistan's second-largest metropolis after Karachi. It covers 1,772 km² between 31°15'–31°43' N and 74°10'–74°39' E. With a history of over 10 centuries. It is on the left bank of Ravi, one of Punjab's five rivers. Lahore has a severe climate with April–September summers. The hottest months are May, June, and July. These months have average minimum and maximum temperatures of 29.3°C and 45.4°C (Almas et al., 2005). Winter runs from November until March. December–February has the coolest weather. These months have mean minimum and maximum temperatures of 7.2°C and 21.1°C. Lahore averages 17.8°C minimum and 30.8°C maximum temperatures. January and February provide light to moderate rainfall to Lahore, followed by excellent spring weather. Since 1951, Lahore's growing urbanization has raised surface and air temperatures. Conversion of vegetation cover to impermeable surface housing developments, industrial and commercial activity, deforestation, GHGS emissions, and vehicle exhausts raise temperatures (Nasar-u-Minallah, 2019).

Faisalabad ranks third in Pakistani population. Between 30°42' and 31°47' North latitudes and 72°40' and 73°40' East longitudes. It is a major industrial center in central Punjab, Pakistan, 130 km west of Lahore. The population of Faisalabad has grown considerably in recent decades. Out of its estimated 6.7 million inhabitants, 40% or 2.7 million live in Faisalabad city, growing at just under 3%. Future birth rates falling below 2% annually. However, Faisalabad is expected to have over 4 million residents by 2025. Faisalabad sits on a level plain with plenty open space for future growth. The city is well-connected to Punjab and Pakistani cities (Bhalli, 2012).

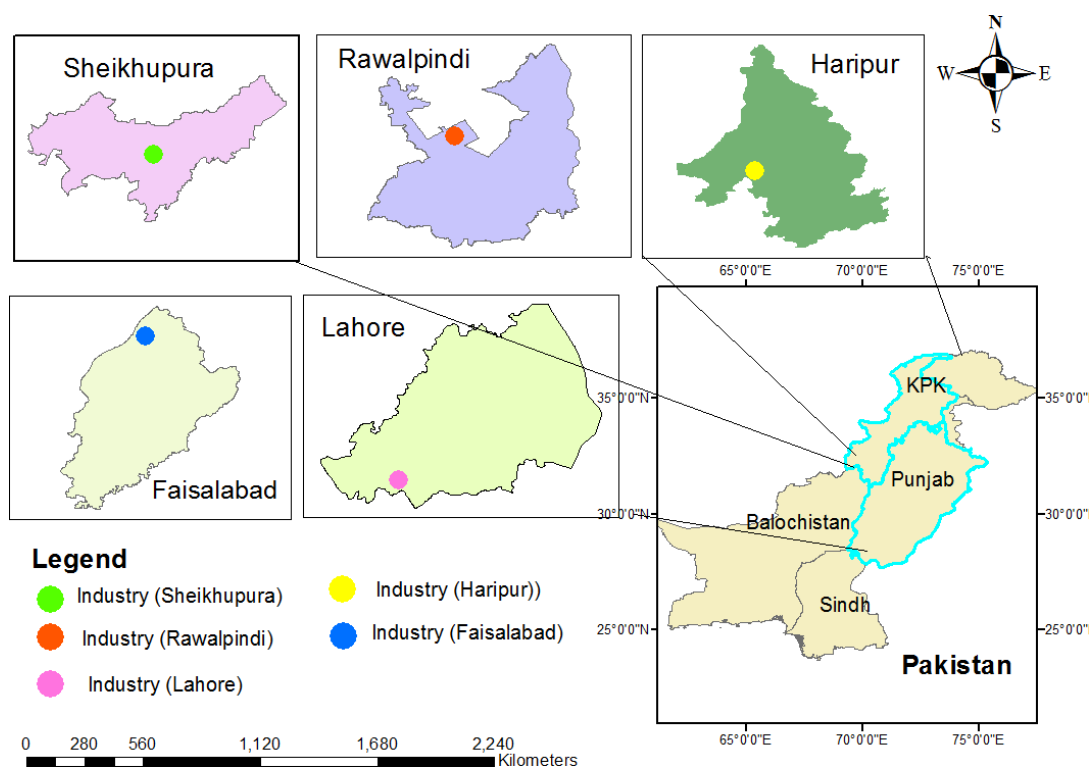


Figure: 2.1: Map of study area, beverage industries across different cities in Pakistan

Table 2.1: Details of sampling sites (beverage industries) across different cities in Pakistan

S. No	Location	Coordinates
1	Rawalpindi	33.58, 73.08
2	Haripur	33.91, 72.79
3	Lahore	31.27, 74.16
4	Sheikhupura	31.68, 74.07
5	Faisalabad	31.61, 73.17

2.2 Research design

The research adopted a comparative, mixed methods research design to evaluate the environmental impacts of five beverage industries. By integrating quantitative measurement of ambient air and stack emissions with qualitative assessments of operational practices, the study aimed to determine each industry's contribution to greenhouse gas emissions and global warming potential. The quantitative components involved the use of instruments and software such as The HORIBA Air Quality Monitoring Stations (AQMS) and LANCOM 4, a software tool used for environmental monitoring, particularly in the context of air quality, industrial emissions, and environmental assessment under US EPA standards ensuring precision and comparability across sites. The qualitative component supplemented these findings by contextualizing emission patterns with industry specific operational data and environmental management strategies.

2.3 Analytical Procedures

2.3.1 Ambient Air Quality Monitoring

Ambient air quality at each facility was monitored for a continuous 24-hour period using HORIBA AQMS stations. Ambient air quality was monitored at mutually agreed sampling points. The ambient air quality was monitored for 24 hours at individual sampling point location from each industry. Data was supported by meteorological variables such as wind speed, temperature, and humidity. Sampling inlets were placed 10 feet above the ground to capture representative air quality. The following parameters will be monitored:

Table 2.2: Detail of parameters measured to assess the ambient air quality

Sr. #	Air Pollutant	Monitoring Technique	Method
01	Carbon Monoxide (CO)	Cross Flow Modulation, non-dispersive infrared (NDIR) absorption technology	US EPA Designated Method RFCA-0981-054
02	Sulphur Dioxide (SO ₂)	UV fluorescence (UVF)	US EPA Designated Method EQSA-0486-060
03	Nitrogen Dioxide (NO _x)	Cross flow modulation type, reduced pressure chemiluminescence (CLD)	US EPA Designated Method RFNA-1289-074
04	Lead	High Volume Sampler	40 CFR 50, App. J (US-EPA)
05	Particulate Matter (PM _{2.5})	β-Ray Absorption Method	40 CFR 50, App. B (US-EPA)
06	Particulate Matter (PM ₁₀)	β-Ray Absorption Method	40 CFR 50, App. B (US-EPA)
07	Total Suspended Particles (TSP)	High Volume Sampler	40 CFR 50, App. J (US-EPA)
08	Ozone	Non-Dispersive UV method.	US EPA Designated Method.

2.3.2 Gaseous Emissions Monitoring

Stack emissions were analyzed using the LANCOM 4 portable gas analyzer. Measurements included CO, CO₂, SO₂, NO_x, PM, and O₂. The probe was calibrated, inserted into the stack, and emissions data was recorded after oxygen stabilization. Five (05) samples were taken from stacks at each industry, three (03) from generators and two (02) from boilers respectively. Measurements followed US EPA-approved methods for accuracy. In accordance with scope of works, following parameters were monitored from the stacks for emissions estimation:

Table 2.3: Parameters measured from stacks for emission estimation

Sr. No.	Parameters	Methodology
01	Oxides of Nitrogen (NO and NO _x)	US EPA Method 7
02	Oxide of Sulfur (SO ₂)	US EPA Method 6 C
03	Oxygen (O ₂)	USEPA CTM-034/3A
04	Carbon Monoxide	USEPA 10
05	Smoke	Ringal man scale
06	Particulate Matter	US EPA Method 5.

2.3.3 Global Warming Potential

The GWP of emitted gases were calculated using IPCC guidelines. Emissions of CO₂, CH₄, and N₂O were converted to CO₂-equivalents using their respective GWP factors (CO₂=1, CH₄=28–34, N₂O=265–298) over a 100-year horizon. This enabled the comparison of climate impact and potential across five industries (Smith et al., 2021).

The mass emission rate (MER) of a pollutant was calculated by multiplying its concentration with the volumetric flow rate of a stack gas. By combining the equation, the mass emission rate was directly calculated from the PPM value, where Mw represents the molecular weight and Q represents the volumetric flow rate of a dry stack gas.

$$m'(\text{kg/h}) = \text{Con}(\text{g/m}^3) \times Q(\text{m}^3/\text{h}) / 1000 \quad (1)$$

$$m'(\text{kg/h}) = \text{ppm} \times \text{MW} / 24.45 \times 10^6 \times Q(\text{m}^3/\text{h}) \quad (2)$$

Procedure

1. Gas concentration from parts per million (ppm) were converted to mass concentration expressed in grams per cubic meter (g/m³).
2. To determine the mass emission rate (g/hr or kg/hr), the exhaust volumetric flow (m³/hr) was multiplied by the appropriate conversion factor.
3. The CO₂ equivalent for each gas was calculated by multiplying its mass by the corresponding Global Warming Potential over a 100-year period.
4. The overall emissions of gases, total CO₂ eq (kg CO₂-eq/hr) was determined.

$$\text{Total CO}_2\text{e (kg h}^{-1}\text{)} = \sum_{i=1}^n m_i \times \text{GWP}_i \quad (3)$$

The formula above was used to calculate the GWP, where m_i represents the mass emission rate of gas in kg per hour and GWP_i denotes the global warming potential of gas relative to CO₂. Carbon dioxide equivalent for few gases is taken as for methane it is 28, for nitrous oxide it is taken 265.

2.4 Sampling instruments

2.4.1 High Volume air sampler

A high-volume air sampler is required for air quality assessment, which affects public health and climate change. This sophisticated gadget measures airborne particles, helping monitor and improve air quality. It is commonly employed to measure PM 10, 2.5 and total suspended particles (TSP). It features an air inlet that captures high-volume ambient air. A filter holder designed to accommodate pre-weighed glass fiber filters. A hoover pump that guarantees consistent airflow. Timer and rotameter to regulate and monitor flow rate and sample period. Weatherproof enclosure that safeguards components in outside environments (Kalisa et al., 2022).

2.4.2 LANCOM 4 Gas analyzer

Lancom 4 is a gas analyzer characterized by a durable casing, extended battery longevity, and integrated data logging capabilities. Lancom 4 provides a comprehensive solution for portable flue gas analysis, encapsulated in a compact, battery-operated device capable of simultaneously measuring up to eight gases with nine distinct sensors. It is

equipped with a sampling probe that extracts flue gases. Heated sample line that inhibits the condensation of gas samples. Sensors for the detection and recording of electrochemical and NDIR measurements for CO, NO_x, SO₂, CO₂, and O₂. Pump System which Draws sample through analyzer. Calibration Module offering zero and span calibration. Lastly real-time data visualization and USB export functionality (ElSharkawy, and Ibrahim, 2022).

2.4.3 HORIBA AQMS

The Horiba AP-380 Ambient Air Quality Monitoring System (AAQMS) employs trace concentration gas measurement technology, developed by HORIBA over 60 years in air pollution monitoring, to facilitate high-sensitivity continuous measurements in the ppb to ppm range. It incorporates an air inlet that draws ambient air from a height of 10 feet. It encompasses gas analyzers such as Carbon Monoxide (Non-Dispersive Infrared), Nitrogen Oxides (Chemiluminescence Detection), Sulphur Dioxide (Ultraviolet Fluorescence), Ozone (Ultraviolet Photometry).

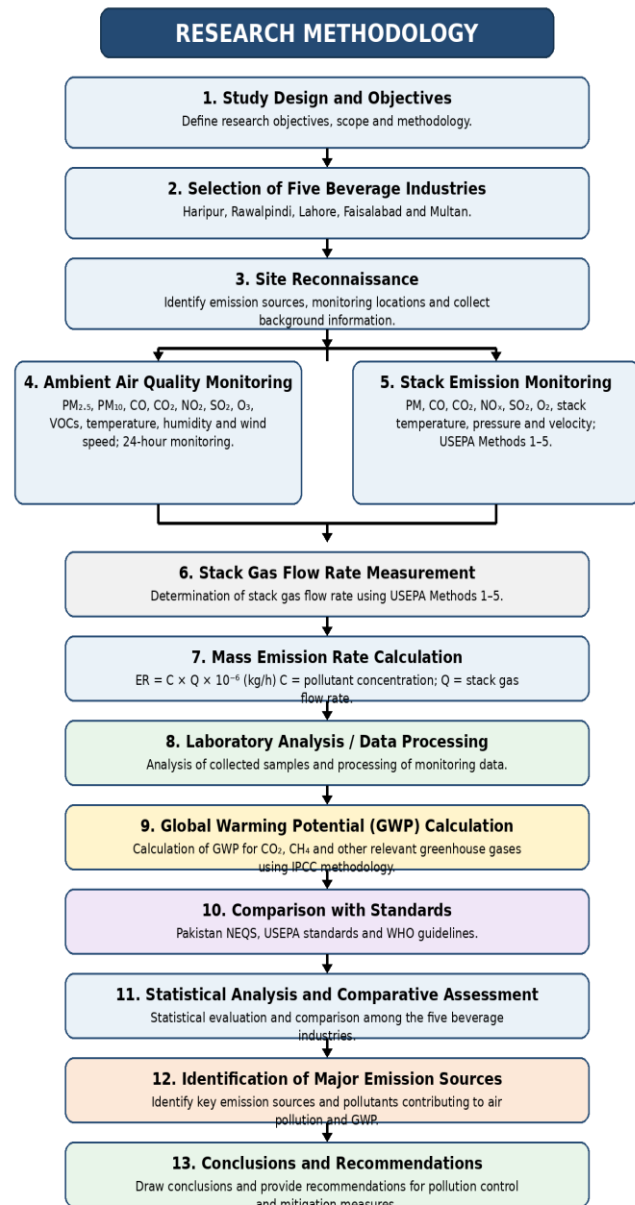


Figure: 2.2: Flowchart of Research Methodology,

2.5 Sampling procedures

High Volume Air Samplers (HVAS) were employed to gather particulate matter samples using pre-weighed filters. Filters were re-weighed after 24 hours to ascertain particle content. LANCOM 4 probes were put into exhaust stacks for stack sampling following the calibration of the analyzer. Real-time measurements were documented and exported for analysis.

Starting the Generation Process required turning on the analyzers with electricity. Stable power and working equipment were guaranteed. After turning on, the analyzers were linked to the probe. The probe pulled air from the environment. The probe was 10 feet high. This height kept ground-level contaminants and local sources out of the air sample, ensuring its representativeness. Data cables or wireless connections connected the analyzers to the laptop. This enabled real-time data monitoring and recording. The laptop analyzer-interfacing software was launched. On opening, the program showed real-time values for air quality metrics like PM, SO₂, NO_x, and other contaminants. Data collecting intervals were adjustable using the software. The level of information and time range needed for analysis determined whether it recorded results each second, minute, or hour. The weather station collects temperature, humidity, wind speed, and direction data. This data helped determine how weather affects air quality. The High-Volume Sampler (HVS) was built to gather airborne PM. The filter paper was weighed on an accurate balance before being placed in the HVS. This allowed PM levels to be determined by measuring particle weight on the filter after sampling. The HVS vent was opened to allow airflow and sampling began. The apparatus was calibrated and the filter paper was secured. After setting up and calibrating, sampling began. The HVS sucked air in, and the filter paper gathered particulates over the sampling period. After sample, the filter paper was

Removed and reweighed. The increase in weight represents particle materials collected during sampling. The laptop program showed real-time air quality data from the analyzers.

Stack Emission Monitoring required connecting the probe to the Lancom 4 analyzer via the right pipe. To avoid data leaks and errors, the probe was securely attached. After connecting the probe, Lancom 4 was turned on. After powering on the device, the fuel setting was set based on the combustion fuel (natural gas, coal, oil, etc.). This procedure was essential for precise measurements and calibration. To ensure accurate reading, the device was zero calibrated. Environmental influences were accounted for by zero calibration at the monitoring station. About 2 minutes were spent on calibrating. Before continuing, the system was zeroed. After calibration, the probe was put into the exhaust stack at the correct sample location, usually the top. For reliable readings, the probe was securely positioned and aligned with gas flow. After positioning the probe, the instrument's start button was pressed to commence monitoring. The system began tracking contaminants in stack emissions, including CO, CO₂, NO_x, SO₂, and particulate matter.

Real-time results appeared on the screen when the equipment examined flue gases. The display was checked for system problems and consistent readings. After stabilizing the system, oxygen (O₂) levels were monitored. The oxygen value was crucial for gas concentration calibration and analysis. After oxygen stabilized, all monitored gases (oxygen, carbon monoxide, carbon dioxide, nitrogen oxides, Sulphur dioxide, etc.) and other emissions parameters were recorded. Once data was collected, the probe was gently removed from the exhaust stack. Avoiding probe contamination and damage was important. The instrument's data was evaluated and compared to air quality standards or emission limits to assess the stack's environmental impact after monitoring.

2.6 Data analysis

Data from all instruments were exported in CSV/Excel format and subjected to descriptive statistical analysis. Arc Map 10.7 Version was used for making any graphical representation. Pollutant concentrations were evaluated in relation to Pakistan's National Environmental Quality Standards (NEQS) (Sial, 2018).

CHAPTER 3

RESULTS AND DISCUSSION

This chapter presents and discusses the ambient air quality and stack emission results obtained from five beverage industries in Pakistan and evaluates their global warming potential. Parameters such as NO_x, NO, Smoke, O₂, N₂O, SO_x, PM, CO, CO₂ were evaluated from the boilers and generators of stacks from the selected industries. Other parameters such as temperature, wind direction, wind speed, atmospheric pressure, noise, humidity, PM 2.5, PM 10, CO, SO₂, O₃, NO, NO₂ and NO_x were also evaluated in the ambient air. The results are presented and discussed in the following sections:

3.1 Ambient air quality of beverage industries

Parameters such as temperature, wind direction, wind speed, atmospheric pressure, noise, humidity, PM 2.5, PM 10, CO, SO₂, O₃, NO, NO₂ and NO_x were also evaluated in the ambient air from each of the five beverage industries. The results of these parameters for each industry are discussed separately given below. Twenty-four (24) readings were taken for the evaluated parameters and then were represented in the form of mean and SD.

3.1.1 Faisalabad beverage industry

The predominant wind directions were west and southwest. The levels of PM 10 and PM 2.5 were within the permissible limit (23.67 ± 3.43 and 121.38 ± 10.08) given by Pak NEQs for national ambient air quality standards. Other parameters such as CO (0.85 ± 0.10), NO₂ (23.43 ± 1.50), O₃ (16.82 ± 1.75) and SO₂ (16.56 ± 2.23) were also within the permissible limits.

Parameters	Mean levels $\pm$ SD	Safe limits
Wind Speed (m/s)	1.64 $\pm$ 0.53	
Temperature (°C)	30.29 $\pm$ 3.21	22.8 to 26.1 °C
Humidity (% RH)	44.67 $\pm$ 8.48	30% to 65%
Atm. Pressure (hPa)	755.25 $\pm$ 0.65	1013.25
Noise (dB)	63.14 $\pm$ 2.34	70 dBA
PM 2.5 ($\mu\text{g}/\text{m}^3$)	23.67 $\pm$ 3.43	35
PM 10($\mu\text{g}/\text{m}^3$)	121.38 $\pm$ 10.08	150
CO (mg/m^3)	0.85 $\pm$ 0.10	5
SO ₂ ($\mu\text{g}/\text{m}^3$)	16.56 $\pm$ 2.23	120
O ₃ ($\mu\text{g}/\text{m}^3$)	16.82 $\pm$ 1.75	180
NO ($\mu\text{g}/\text{m}^3$)	13.46 $\pm$ 0.95	
NO ₂ ($\mu\text{g}/\text{m}^3$)	23.43 $\pm$ 1.50	80
NOx ($\mu\text{g}/\text{m}^3$)	36.90 $\pm$ 1.67	

Table 3.1: levels of parameters in ambient air of FSB beverage industry

3.1.2 Lahore beverage industry

Table 3.2: levels of parameters in ambient air of LHR beverage industry

Parameters	Mean levels $\pm$ SD	Safe limits
Wind Speed (m/s)	0.98 $\pm$ 0.29	
Temperature (°C)	30.20 $\pm$ 2.92	22.8 to 26.1 °C
Humidity (% RH)	56.42 $\pm$ 4.35	30% to 65%
Atm. Pressure (hPa)	752.25 $\pm$ 0.65	1013.25
Noise (dB)	46 $\pm$ 5.04	70 dBA
PM 2.5 ($\mu\text{g}/\text{m}^3$)	26.67 $\pm$ 3.43	35
PM 10($\mu\text{g}/\text{m}^3$)	122.6 $\pm$ 9.78	150
CO (mg/m^3)	0.85 $\pm$ 0.10	5
SO ₂ ($\mu\text{g}/\text{m}^3$)	16.15 $\pm$ 2.23	120
O ₃ ($\mu\text{g}/\text{m}^3$)	16.72 $\pm$ 1.75	180
NO ($\mu\text{g}/\text{m}^3$)	9.66 $\pm$ 0.95	
NO ₂ ($\mu\text{g}/\text{m}^3$)	18.33 $\pm$ 1.50	80
NOx ($\mu\text{g}/\text{m}^3$)	28 $\pm$ 1.67	

The direction of wind speed was majorly south. The levels of PM 10 and PM 2.5 were within the permissible limit (26.67 $\pm$ 3.43 and 122.6 $\pm$ 9.78) given by Pak NEQs for national ambient air quality standards. Other parameters such as CO (0.85 $\pm$ 0.10), NO₂ (18.33 $\pm$ 1.50), O₃ (16.72 $\pm$ 1.75) and SO₂ (16.15 $\pm$ 2.23) were also within the permissible

limits.

3.1.3 Sheikhupura beverage industry

Table 3.3: levels of parameters in ambient air of Sheikhupura beverage industry

Parameters	Mean levels $\pm$ SD	Safe limits
Wind Speed (m/s)	1.4 $\pm$ 0.5	

Temperature (°C)	24.6±4.3	22.8 to 26.1 °C
Humidity (% RH)	48.2±9.3	30% to 65%
Atm. Pressure (hPa)	758.9± 0.6	1013.25
Noise (dB)	57± 3.9	70 dBA
PM 2.5 (µg/m³)	30.9± 3.9	35
PM 10(µg/m³)	133±7.3	150
CO (mg/m³)	1.1± 0.3	5
SO₂(µg/m³)	18.5± 4.7	120
O₃(µg/m³)	15.6± 3.0	180
NO (µg/m³)	13.3± 2.3	
NO₂(µg/m³)	26.6± 4.6	80
NO_x (µg/m³)	40± 3.8	

The direction of wind speed was majorly northwest and north for most of the readings taken at different time intervals. The levels of PM 10 and PM 2.5 were within the permissible limit (30.9± 3.9 and 133±7.3) given by Pak NEQs for national ambient air quality standards. Other parameters such as Carbon monoxide (CO) (1.1± 0.3), NO₂ Nitrous oxide (26.6± 4.6), Ozone (O₃) (15.6± 3.0) and Sulphur dioxide (SO₂) (18.5± 4.7) were also within the permissible limits.

3.1.4 Haripur beverage industry

Table 3.4: levels of parameters in ambient air of Haripur beverage industry

Parameters	Mean levels ± SD	Safe limits
Wind Speed (m/s)	1.7±0.6	
Temperature (°C)	32±3.6	22.8 to 26.1 °C
Humidity (% RH)	51.9±5.9	30% to 65%
Atm. Pressure (hPa)	752.3± 0.7	1013.25
Noise (dB)	65± 2.6	70 dBA
PM 2.5 (µg/m³)	30.0± 3.8	35
PM 10(µg/m³)	135.4±9.0	150
CO (mg/m³)	1.4± 0.4	5
SO₂(µg/m³)	34.8± 11.2	120
O₃(µg/m³)	19.0± 3.5	180
NO (µg/m³)	14.3± 2.6	
NO₂(µg/m³)	23.6± 4.6	80
NO_x (µg/m³)	38± 5.2	

The predominant wind directions were northeast and east for most of the readings taken at different time intervals. The levels of PM 10 and PM 2.5 were within the permissible

limit (30.0 ± 3.8 , and 135.4 ± 9.0) given by Pak NEQs for national ambient air quality standards. Other parameters such as Carbon monoxide (CO) (1.4 ± 0.4), NO₂ Nitrous oxide (23.6 ± 4.6), Ozone (O₃) (19.0 ± 3.5) and Sulphur dioxide (SO₂) (34.8 ± 11.2) were also within the permissible limits.

3.1.5 Rawalpindi beverage industry

Table 3.5: levels of parameters in ambient air of RWP beverage industry

Parameters	Mean levels $\pm$ SD	Safe limits
Wind Speed (m/s)	1.5 ± 0.6	
Temperature (°C)	42.0 ± 3.6	22.8 to 26.1 °C
Humidity (% RH)	31.9 ± 5.9	30% to 65%
Atm. Pressure (hPa)	747.3 ± 0.7	1013.25
Noise (dB)	66.2 ± 2.6	70 dBA
PM 2.5 ($\mu\text{g}/\text{m}^3$)	29.0 ± 3.8	35
PM 10($\mu\text{g}/\text{m}^3$)	134.4 ± 9.0	150
CO (mg/m^3)	1.3 ± 0.4	5
SO ₂ ($\mu\text{g}/\text{m}^3$)	32.5 ± 11.2	120
O ₃ ($\mu\text{g}/\text{m}^3$)	18.0 ± 3.5	180
NO ($\mu\text{g}/\text{m}^3$)	15.6 ± 2.6	
NO ₂ ($\mu\text{g}/\text{m}^3$)	25.9 ± 4.6	80
NOx ($\mu\text{g}/\text{m}^3$)	41.6 ± 5.3	

The direction of wind speed was majorly northeast, and east for most of the readings taken at different time intervals. The levels of PM 2.5 and PM 10 were within the permissible limit (29.0 ± 3.8 , and 134.4 ± 9.0) given by Pak NEQs for national ambient air quality standards. Other parameters such as Carbon monoxide (CO) (1.3 ± 0.4), NO₂ Nitrous oxide (25.9 ± 4.6), Ozone (O₃) (18.0 ± 3.5) and Sulphur dioxide (SO₂) (32.5 ± 11.2) were also within the permissible limits.

Similar findings were reported by Dhada et al. (2025), who found the highest values of PM 10 ($359 \mu\text{g}/\text{m}^3$), 2.5 ($102 \mu\text{g}/\text{m}^3$) and noise (87 dB) within the 12 bottling beverage industries of Himanchal Pradesh India. Idress et al. (2021) also assessed the ambient air quality of industrial areas in Karachi, and found higher levels of NO_x, SO₂, PM 10 and PM 2.5 during pre-monsoon season as compared to post-monsoon season. Khan et al. (2023) also found pollutant concentrations lower under stringent lockdown and higher during moderate and post-COVID-19 lockdown in Lahore's residential towns. SO₂,

PM₁₀, PM_{2.5}, CO, O₃, and NO₂ increased 100%, 270%, 500%, 300%, 70%, and 115% post-COVID-19. Winter peaked PM₁₀, PM_{2.5}, NO₂, and SO₂ pollution.

3.2 Stack emissions from beverage industries

3.2.1 Faisalabad beverage industry

Table 3.6: Concentrations of parameters in stack emissions from FSB beverage industry

Parameters	Boiler 1	Boiler 2	Generator 1	Generator 2	Generator 3	Safe limits
CO (mg/m ³)	443.67 ±47.5	421.9 ± 32.1	503 ±11	432.3±21.1	420.3±22.4	10
SO ₂ (µg/m ³)	409.33±49.52	392.2 ± 41.3	163.3±11.6	113.0±14.1	76.3±12.1	120
O ₂ (%)	11.53±1.19	10.82 ± 1.42	14.6±0.6	14.5±1.2	14.4±0.7	
NO ₂ (µg/m ³)	24.67±4.51	20.92 ± 3.19	33.3±9.6	25.3±4.5	26.0±2	80
NO (µg/m ³)	273.67±24.91	291.4 ± 27.3	614±25.1	637.7±9.3	633.7±30.7	
NO _x (µg/m ³)	298.33±29.14	317.6 ± 31.9	647.3±34.5	663.0±13.7	659.7±32.6	
CO ₂ (%)	9.57±1.0	9.23 ± 0.85	6.17±0.9	6.8±1.0	6.8±1.1	
PM (µg/m ³)	39.9±0.06	42.15 ± 0.09	60.7±0.6	70.0±1.0	80.3±0.6	35

The highest emissions were recorded at boiler 1 as compared to boiler 2. The average values of parameters were highest in boiler one as compared to boiler 2. The highest values were recorded for CO (443.67 ±47.5), SO₂ (409.33±49.52) were recorded in the boiler 1 whereas for other parameters NO (291.4 ± 27.3), NO_x (317.6 ± 31.9), and PM (42.15 ± 0.09) highest values were recorded in boiler 2. Among the three generators, generator 2 and 3 had the highest rate of emissions. High values of CO (432.3±21.1), NO (637.7±9.3), NO_x (663.0±13.7), and PM (80.3±0.6) were recorded in the generator 2 and 3. All generators and boilers were running on diesel fuel, boilers being on 50% load whereas generators on 70% load. Concentrations of all major pollutants surpassed the permissible limits given by Pak NEQs.

3.2.2 Lahore beverage industry

Table 3.7: Concentrations of parameters from stack emissions in LHR beverage industry

Parameters	Boiler 1	Boiler 2	Generator 1	Generator 2	Generator 3	Safe limits
CO (mg/m ³)	280.33±18.6	340.33±19.5	316±14	277.3±21.2	351±24.8	10
SO ₂ (µg/m ³)	77.67±10.3	-	152±11	164.3±9.1	182±12	120
O ₂ (%)	13.47±0.85	12.6±1.0	15.6±0.7	15.4±1.2	13.7±1.1	
NO ₂ (µg/m ³)	30±5.6	15.3±5.5	21.6±8.5	30.3±4.5	29±6	80
NO (µg/m ³)	317±15.7	210.3±12.6	410.3±9.5	334.3±29.6	398.3±17.6	
NO _x (µg/m ³)	347±21.1	225.7±17.9	432±18	364.7±33.9	427.3±23.6	
CO ₂ (%)	7.43±1.0	8.2±1.03	5.4±0.7	5.6±1.2	7.3±1.1	
PM (µg/m ³)	62.2±0.1	29.5±0.1	80.2±0.05	75.4±0.2	75.7±0.2	35

The results of stack emissions from Lahore beverage industry showed that among the two boilers, boiler 1 had highest rate of emissions as compared to boiler 2. The parameters particularly CO (280.33±18.6), NO (317±15.7), NO_x (347±21.1), and PM (62.2±0.1) had high levels of emissions. The values of these parameters were within the permissible limits given by Pak NEQs. Among the three generators, generator 1 and 3 had highest emissions for the major parameters. NO₂ and CO₂ were within the permissible limits. CO, SO₂, NO, NO_x and PM surpassed the limits in all three generators. All boiler and generators were fully on load, boilers running on natural gas whereas generators on diesel fuel.

3.2.3 Sheikhpura beverage industry

Highest emissions were recorded at boiler 2 as compared to boiler 1. Highest values were recorded for CO (334.3±30.2), SO₂ (121.7±11.1), NO (423.0±13.0), NO_x (458.0±18.0), and PM (89.6±0.1). For the generators, highest emission concentrations were recorded for CO, SO₂, NO, NO_x, and PM with highest values at the generator 3 followed by 1 and 2. Both the boilers were running on natural gas and generators were running on diesel fuel. Both were fully on load. NO₂ and CO₂ were within the permissible limit.

However, parameters such as CO, SO₂, NO, NO_x and PM surpassed the permissible limit for both boilers and generators.

Table 3.8: Concentrations of parameters from stack emissions in Rawalpindi beverage industry

Parameters	Boiler 1	Boiler 2	Generator 1	Generator 2	Generator 3	Safe limits
CO (mg/m ³)	213.7±19.8	334.3±30.2	341.7±9.6	343.3±26.6	411.3±11.1	10
SO ₂ (µg/m ³)	-	121.7±11.1	216.3±29.4	172.7±11.2	215.0±15.0	120
O ₂ (%)	12.6±1.0	14.6±1.3	14.6±0.9	15.5±1.1	13.4±1.0	
NO ₂ (µg/m ³)	20.7	35.0± 5.0	25.7±9.5	32.0±7.2	39.3±6.0	80
NO (µg/m ³)	264.3±14.0	423.0±13.0	364.0±17.1	356.0±15.1	408.3±17.6	
NO _x (µg/m ³)	285.0±24.0	458.0±18.0	389.7±26.4	388.0±22.0	447.7±23.6	
CO ₂ (%)	8.4±1.0	6.5±1.2	6.4±0.9	5.5±1.1	7.6±1.0	
PM (µg/m ³)	45.3±1.0	89.6±0.1	96.7±0.1	91.6±1.0	93.6±1.0	35

3.2.4 Haripur beverage industry

For Haripur beverage industry, boilers were running on natural gas and generators were running on diesel and full-on load. The overall emissions recorded from boilers and generators were not very high. CO₂ and NO₂ were within the permissible limits. CO, SO₂, NO, NO_x, and PM were above the recommended limit given by Pak NEQs. CO (99±4 and 162±11.1), and NO_x had highest values for generators and followed by boilers (179.6±27.06, and 205±15.0). NO had values 167±23.06, highest from boiler 1 and 190 ±10.0 from generator 3.

Table 3.9: Concentrations of parameters from stack emissions in Haripur beverage industry

Parameters	Boiler 1	Boiler 2	Generator 1	Generator 2	Generator 3	Safe limits
CO (mg/m³)	99±4	35.3±3.5	134.3±14.0	144.7±5.7	162±11.1	10
SO₂(µg/m³)	-	-	67.3±5.0	62.7±17.5	84.0±2.0	120
O₂(%)	13.3±1.1	15.6±0.7	14.7±1.6	12.4	11.3±1.1	
NO₂ (µg/m³)	12.6±4.72	15.3±5.0	24.0±11.1	26.3	15.0±5.0	80
NO (µg/m³)	167±23.06	127.3±14.2	179.3±8.3	163.7±9.3	190 ±10.0	
NO_x (µg/m³)	179.6±27.06	142.7±19.2	200.0±15.6	190.0±19.7	205±15.0	
CO₂(%)	7.3±1.05	5.3±1.3	5.9±1.6	8.4±1.2	9.1±0.7	
PM (µg/m³)	32±1	36.0±1.0	83.0±1.0	74.0±1.0	70.0±1.0	35

3.2.5 Rawalpindi beverage industry

For Rawalpindi beverage industry, both of the thermal boilers were fully on load and were running on natural gas as a fuel. The three generators were also fully on load and working on diesel fuel. SO₂ and NO₂ were within the limits given Pak NEQS overall, however CO, NO, NO_x and PM levels surpassed the safe limits. However, the CO, and NO were above the recommended limit (170.7±10.1 and 261.0±17.7).

Table 3.10: Concentrations of parameters from stack emissions in Sheikhpura beverage industry

Parameters	Boiler 1	Boiler 2	Generator 1	Generator 2	Generator 3	Safe limits
CO (mg/m ³)	62.3±11.5	95.7±12.3	116.3±9.1	170.7±10.1	148.0±14.9	10
SO ₂ (µg/m ³)	-	-	54.0±4.6	64.0±14.5	74.0±12.0	120
O ₂ (%)	5.7±1.6	12.8±1.4	12.7±0.9	12.8±1.4	12.5±0.7	
NO ₂ (µg/m ³)	11.0±2.0	15.7±5.0	19.7±4.0	22.3±7.0	36.0±4.6	80
NO (µg/m ³)	121.3±11.0	140.7±11.0	158.3±14.6	210 ±9.5	225.0±13.5	
NO _x (µg/m ³)	132.3±13.0	156.3±16.0	178.0±18.5	232.3 ± 16.5	261.0±17.7	
CO ₂ (%)	9.4±1.0	7.6±1.2	8.3±1.0	8.1±1.3	7.9±1.4	
PM (µg/m ³)	9.5±0.1	12.5±0.1	67.7±0.6	60.7	72.9±0.5	35

For carbon monoxide (CO) highest emission were recorded at the generator 2 and 3 followed by 1. For nitric oxide (NO) highest emission levels were recorded at generator number 3 and 2 followed by 1. NO_x levels were also higher at the boilers as well as at the generators (232.3 ± 16.5 and 261.0±17, maximum for generator 2 and 3).

The findings of stack emissions from five beverage businesses in Pakistan indicated elevated levels of PM, nitrogen oxides, sulfur dioxide, and carbon monoxide. These pollutants are frequently associated with combustion processes utilized in boilers and produced in industrial settings. Elevated concentrations of these pollutants may result from slow or insufficient maintenance of boilers or generators, leading to incomplete combustion that releases these pollutants into the atmosphere (Urbaniak et al., 2015). Additional factors may include substandard fuel quality, such as inferior diesel or natural gas utilized in the boilers. This entity is capable of emitting sulfur dioxide. the inadequate emission control methods such as old scrubbers or filters which may not be working to their full potential. Other reasons can be low atmospheric pressure, and local climate and weather of the area where the industries are located (NCASI, 2004).

Most emissions which are common from boilers and generators are Carbon monoxide (CO), Sulphur dioxide (SO₂), Nitrous oxide (NO₂), and Particulate matter (PM). Sulphur dioxide (SO₂) mainly from Sulphur based fuels (coal, diesel, etc.,) when burned in boilers to power beverage processing operations. PM from ash, dust and drying processes in beverage industries, these release fine particles into the atmosphere. CO is released from incomplete combustion in boilers or furnaces to produce heat or steam. NO and NO₂ are formed at high combustion temperatures when nitrogen reacts with oxygen commonly in industrial facilities and equipment (Lee et al., 2023).

Lee and Mak, (2019) studied Hong Kong research building stack emissions in nearby cities. A year of air monitoring comprised 15 pollutants. Among the 15 pollutants, NO₂, acetonitrile, and TVOC exceeded exposure limits (Lee and Mak, 2019). Hameed and Rahman, (2020) also found high concentrations of NO_x, SO₂ and CO in an electric arc furnace of steel manufacturing industry surpassing NEQs of Pakistan. Choi and Jo (2011) studied industrial emissions of four major and three additional harmful air pollutants in four Yeongnam subareas over five years. Most industries that burn fuel or incinerate trash had the greatest NO_x and SO₂ emissions. Winter and summer had the highest emissions, while spring and fall had the lowest, likely due to increased home and industrial heating and cooling (Choi and Jo, 2011).

3.3 Comparative analysis of ambient air quality (AAQ)

For comparative analysis of ambient air quality each parameter and its concentration was compared across all five industries.

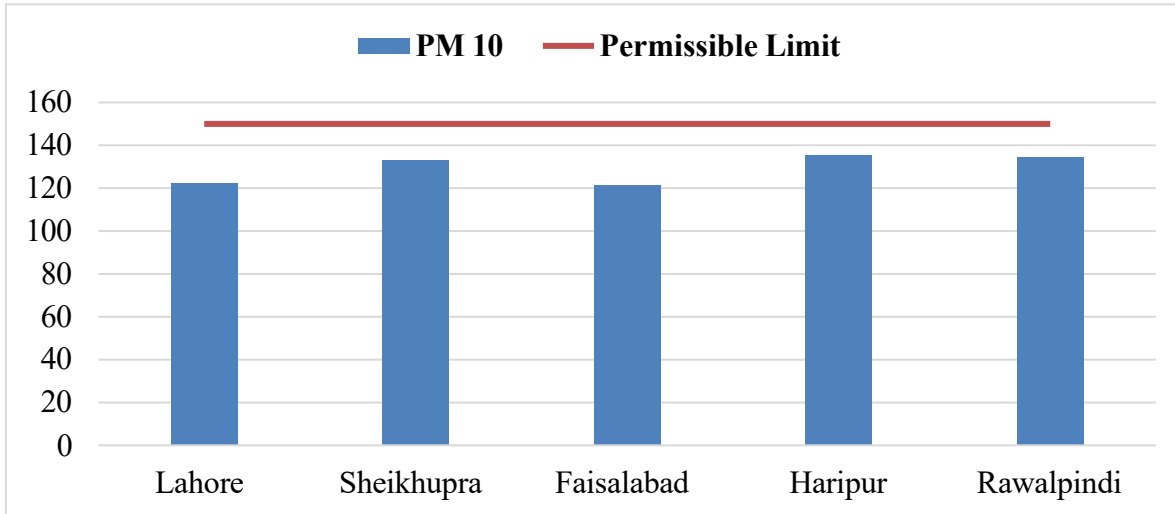


Figure 3.1: Comparison of PM 10 in AAQ across five beverage industries

The concentration of PM 10 in ambient air was within the permissible limit given by Pak NEQs in all beverage industries.

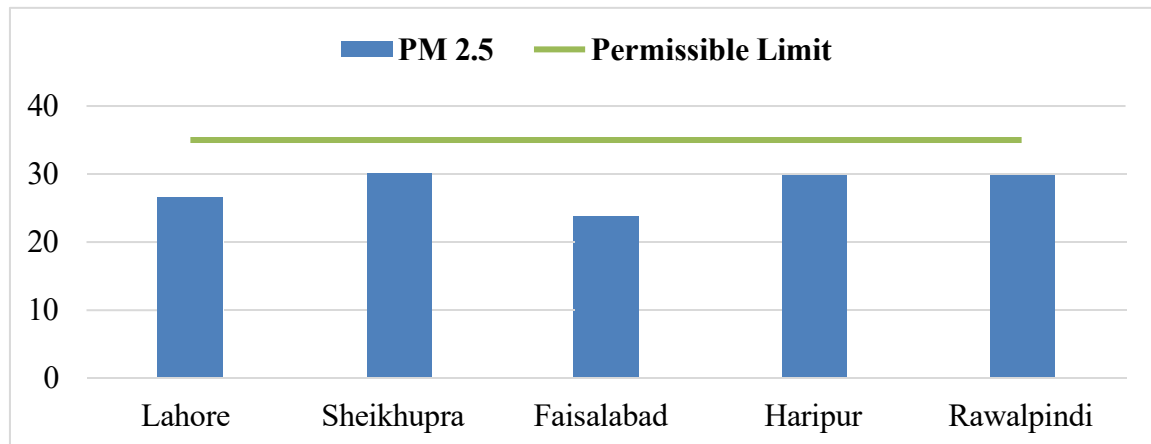


Figure 3.2: Comparison of PM 2.5 in AAQ across five beverage industries

The concentration of PM 2.5 in ambient air was also within the permissible limit given by Pak NEQs in all beverage industries.

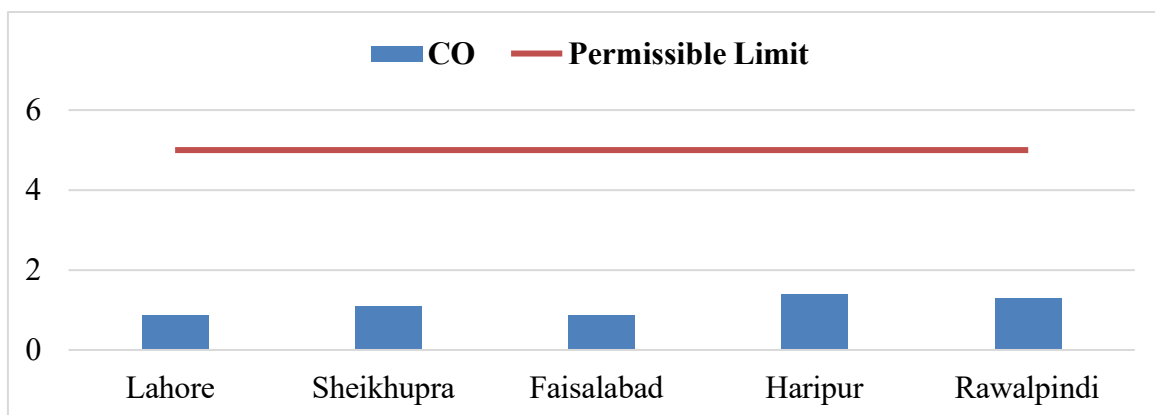


Figure 3.3: Comparison of CO in AAQ across five beverage industries

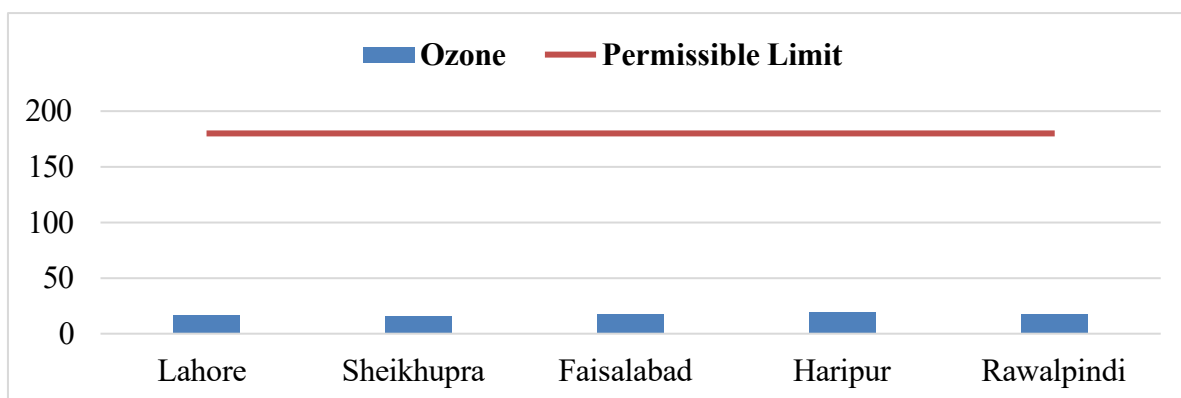


Figure 3.4: Comparison of O₃ in AAQ across five beverage industries

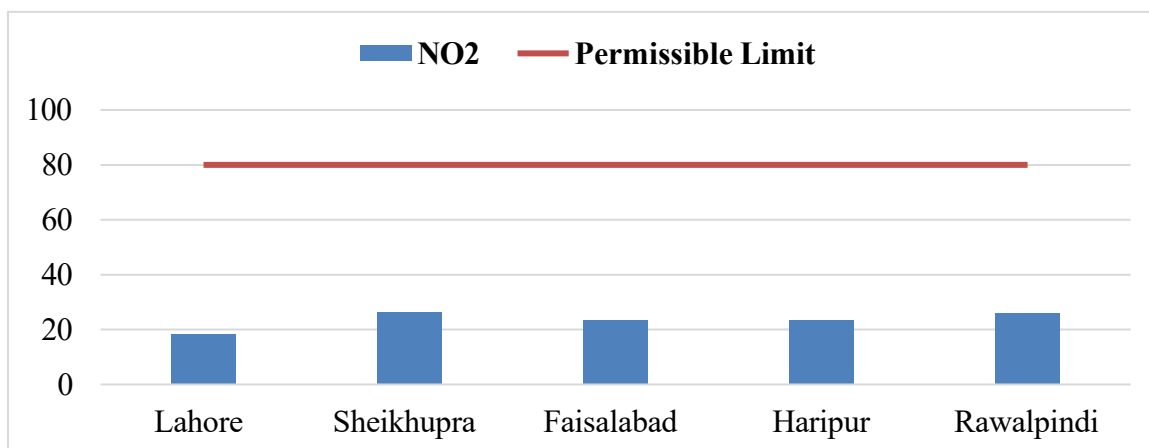


Figure 3.5: Comparison of NO₂ in AAQ across five beverage industries

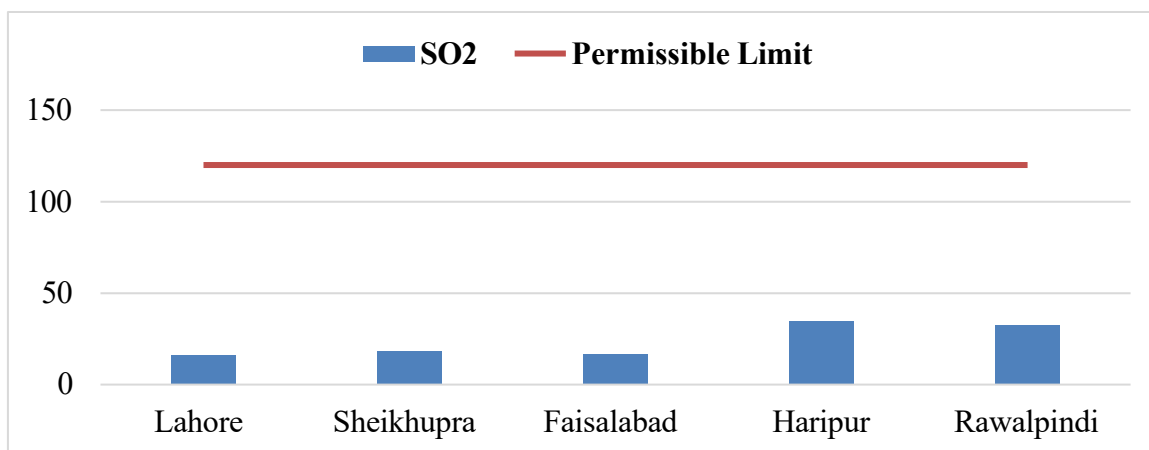


Figure 3.6: Comparison of SO₂ in AAQ across five beverage industries

The concentrations of CO, NO₂, SO₂, and Ozone (O₃) in ambient air were all within the permissible limit given by Pak NEQs in five beverage industries.

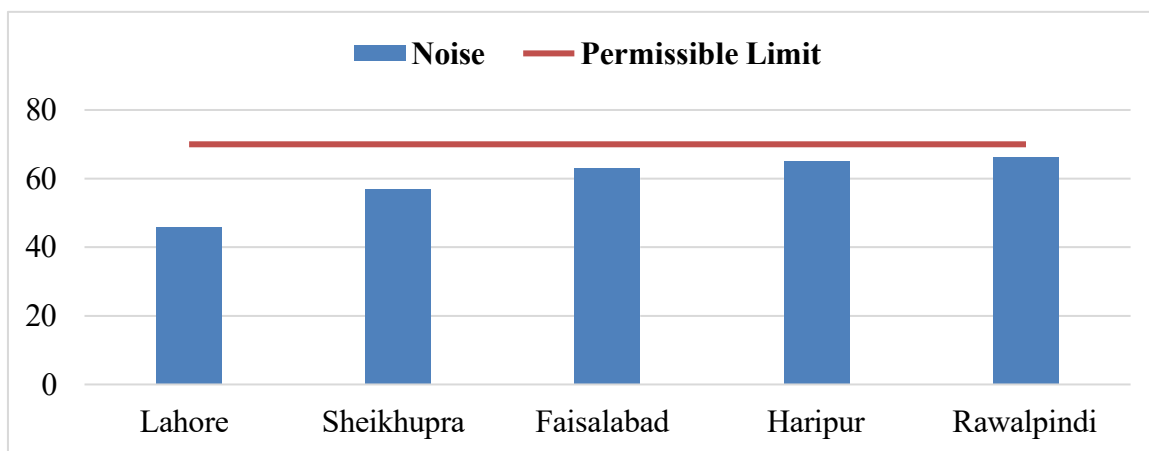


Figure 3.7: Comparison of Noise in AAQ across five beverage industries

The noise levels were in the decreasing order Rawalpindi > Haripur > Faisalabad > Sheikhupura > Lahore. The noise was significantly higher which can be due to loud machinery operations, and process equipment's in beverage industries. However, the levels were within the limit by WHO.

3.4 Comparative analysis of stack emissions

3.4.1 Boilers

The parameters assessed in all boilers (two) across five beverage industries were compared and shown in graphs separately.

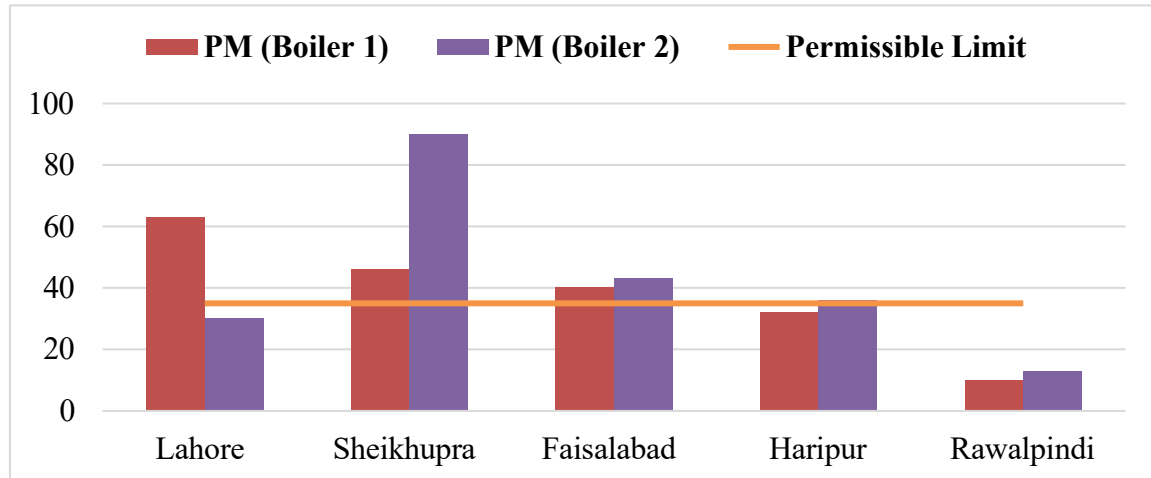


Figure 3.8: Comparison of PM in boilers across five beverage industries

For Lahore boiler 1 had surpassed the safe limit for PM emissions whereas the boiler 2 had PM emissions within the safe limit of 35 $\mu\text{g}/\text{m}^3$. For Sheikhupura and Faisalabad both the boilers had PM levels surpassing the safe limit. Rawalpindi boilers had PM levels within the safe limit. For Haripur boiler 1 levels were within the safe limit whereas boiler had surpassed the safe PM limit. Incomplete combustion of fuel, poor fuel quality and insufficient pollution control devices can lead to PM generation from boilers.

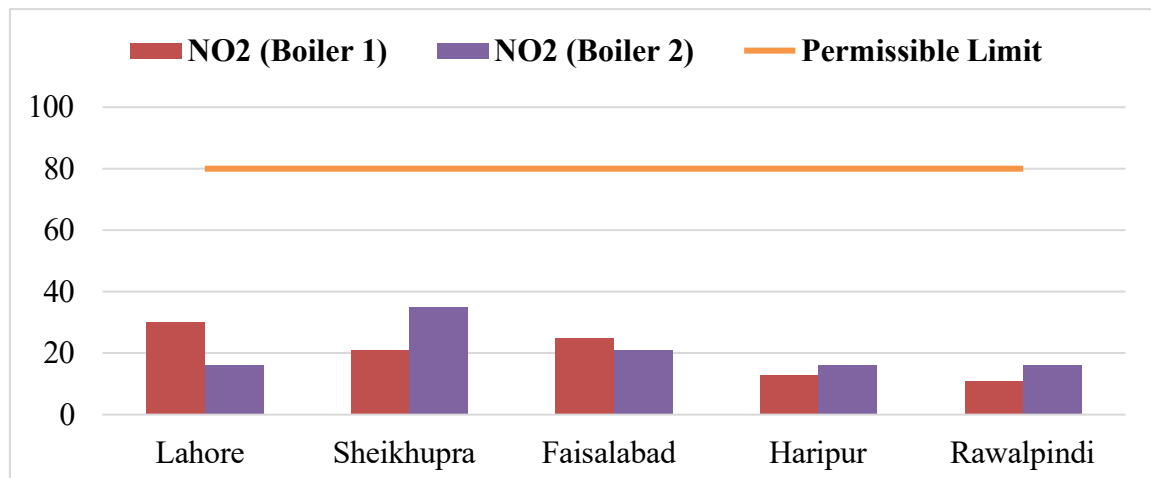


Figure 3.9: Comparison of NO₂ in boilers across five beverage industries

The levels of NO₂ emissions in all five beverage industries from stacks (boilers) were within the acceptable limit given by Pak NEQs.

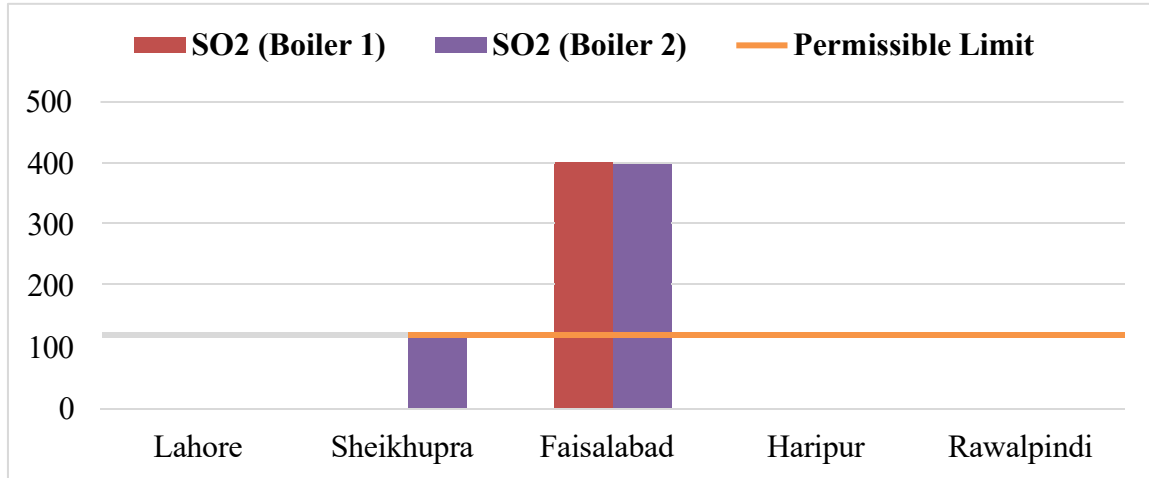


Figure 3.10: Comparison of SO₂ in boilers across five beverage industries

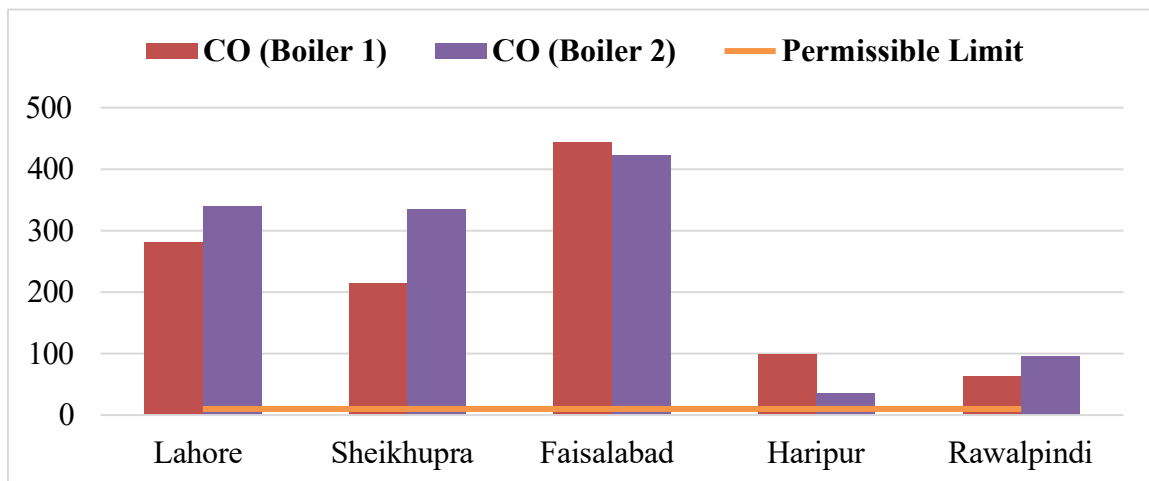


Figure 3.11: Comparison of CO in boilers across five beverage industries

The levels of CO emissions from boilers of all beverage industries surpassed the recommended limit given by Pak NEQs. The incomplete combustion of fuels particularly improper fuel ratios and combustion temperatures can lead to higher CO emissions. Poor maintenance of furnaces and control systems can also result in higher emissions.

3.4.2 Generators

The parameters assessed in all three generators across five beverage industries were compared and shown in graphs separately.

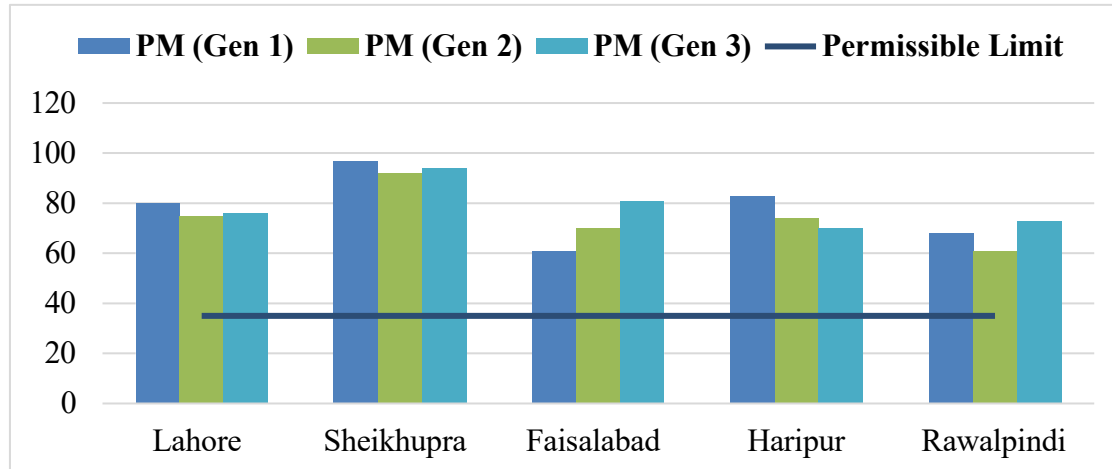


Figure 3.12: Comparison of PM from generators across five beverage industries

All generators had PM emission levels surpassing the acceptable limit given by Pak EPA. Incomplete combustion of fuel, poor fuel quality and insufficient pollution control devices can lead to PM generation from boilers. The major reason is the usage and combustion of diesel fuel with inadequate air-fuel mixing ratios leading to particulate matter formation.

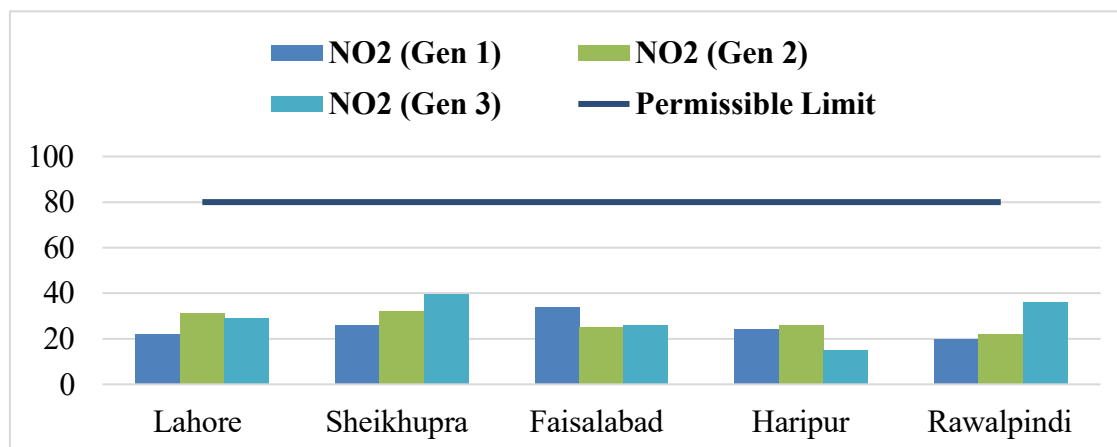


Figure 3.13: Comparison of NO₂ from generators across five beverage industries

The levels of NO₂ emissions in all five beverage industries from stacks (generators) were within the acceptable limit given by Pak NEQs.

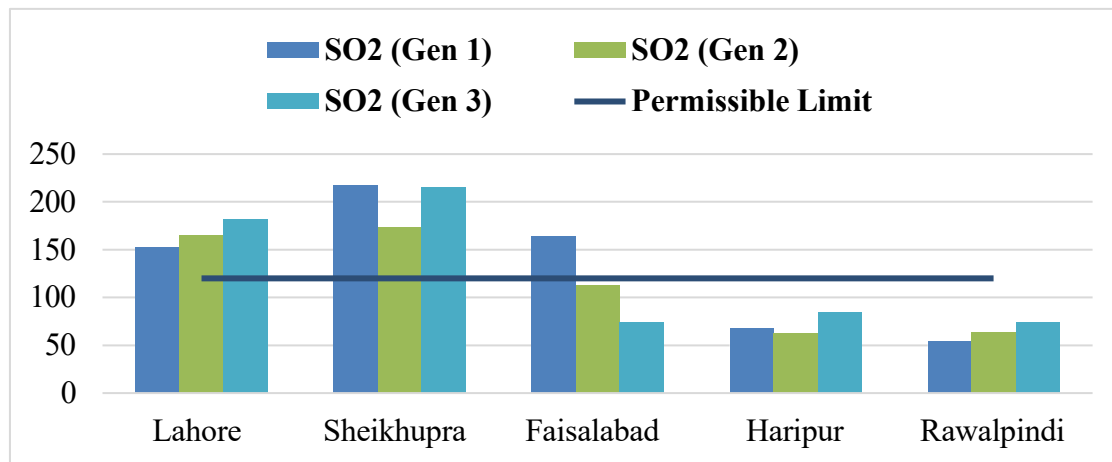


Figure 3.14: Comparison of SO₂ from generators across five beverage industries

As the generators were working on diesel fuel, it has more Sulphur content whereas diesel fuel has Sulphur content therefore higher SO₂ emissions were recorded for Lahore, Sheikhupura and Faisalabad surpassing the acceptable level given by Pak NEQs. Rawalpindi and Haripur had SO₂ levels within the safe limits.

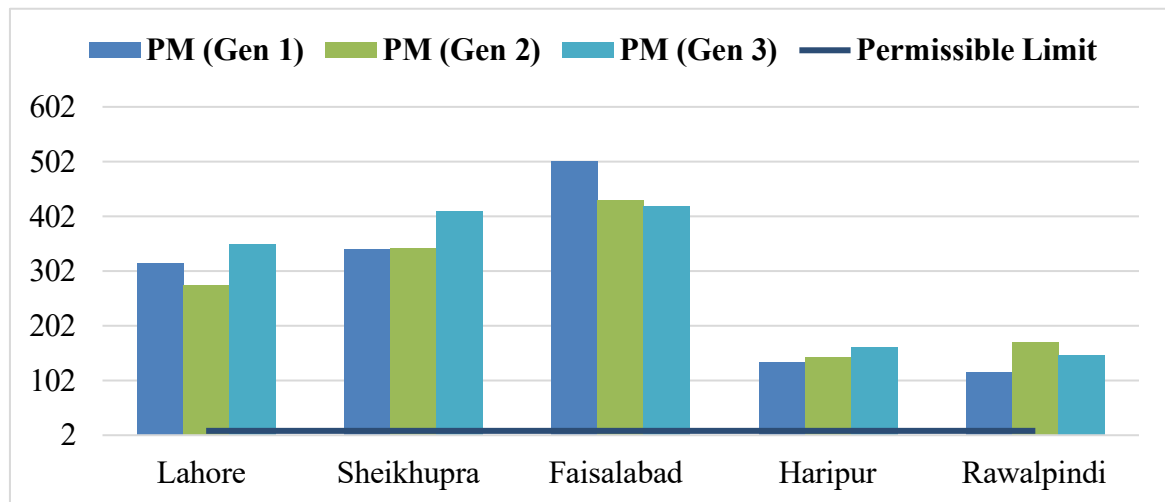


Figure 3.15: Comparison of CO from generators across five beverage industries

The levels of CO emissions from three generators of all beverage industries surpassed the recommended limit given by Pak NEQs. The incomplete combustion of fuels

particularly improper fuel ratios and combustion temperatures can lead to higher CO emissions. Poor maintenance of generators running on diesel majorly and poor control systems can also result in higher carbon monoxide emissions.

Similar to the emissions from generators, Jakhrani et al. (2012) also found that carbon net emissions increase five times when net emissions increased from 1 to 5kg CO₂ per liter. Natural gas and Diesel dual fuel operations usage in boilers and generators can reduce CO₂ and NO₂ but it may increase PM and CO emissions. Natural gas has less carbon content than diesel therefore, more emissions can come from diesel. NO_x emissions from natural gas are lower due to cleaner combustion and lower flame temperature whereas in diesel there are more No_x emissions because of higher combustion temperatures. For SO₂ natural gas has little or no Sulphur content as compared to diesel. Older forms of diesel have higher Sulphur content therefore more SO₂ emissions. For PM natural gas emits very lower PM (burns cleanly with little ash) as compared diesel (incomplete combustion and more hydrocarbon content). For CO natural emits lower carbon monoxide emissions due to efficient combustion whereas in diesel there are higher emissions due to incomplete combustion especially in generators working under varying loads (Wei and Geng, 2016).

3.5 Global Warming Potential (GWP)

The GWP was calculated on the basis of stack emissions from five beverage industries in terms of CO₂ eq. The tables below show the results of GWP in terms of CO₂ eq calculated for each industry based on emissions sources, boilers and generators. These results show the relative contribution of different combustion sources within a beverage industry to global warming potential expressed as carbon dioxide equivalent from stack emissions.

3.5.1 Faisalabad

Table 3.11: Total CO₂-eq (kg/m³) calculated for Faisalabad beverage industry

Source	CO ₂ (%)	Total CO ₂ -eq (kg/m ³)
Boiler 1	9.57	0.172
Boiler 2	9.23	0.166
Generator-1	6.17	0.111

Generator-2	6.80	0.123
Generator-3	6.80	0.122

The boilers had highest CO₂ concentrations and equivalent values among all sources. Boiler 1 had the highest values followed by Boiler 2 at 9.57% and 0.17 kg per m³. The higher values are mainly due to continuous operation, higher fuel usage, and combustion for the heat generation, which is very common in beverage manufacturing for washing, heating, and bottling process. The generators had comparatively lower CO₂% and eq value ranging from 0.11 to 0.12 kg per m³. This may due to the continuous working, and lower fuel usage as compared to boilers. Generator 1 had shown lower impact compared to 2 and 3, which can be due to better combustion efficiency, shorter operation time and overall lower load. Generator 2 and 3 had same values which can be due to same engine capacity, fuel type and loading conditions. This facility had shown that only boilers had the highest potential to global warming based on CO₂ eq values.

3.5.2 Lahore

Table 3.12: Total CO₂-eq (kg/m³) calculated for Lahore beverage industry

Source	CO ₂ (%)	Total CO ₂ -eq (kg/m ³)
Boiler 1	7.43	0.1342
Boiler 2	8.20	0.1481
Generator-1	5.4	0.0977
Generator-2	5.6	0.1013
Generator-3	7.3	0.1318

The results showed that boilers had highest CO₂ % and eq values, boiler 2 had higher values (CO₂ % 7.43 and CO₂ eq 0.134) followed by boiler 1. This showed that boilers were the main contributors to CO₂ equivalent emissions in this beverage industry, which can be related to continuous operation and higher fuel use for heating, processing, and steam generation. Generator 3 had the highest CO₂ % and eq values compared to 2 and 1. This can be due longer running time, more fuel burning, and operation at higher load. This facility had shown that both boilers, and generators had the potential to global warming based on CO₂ eq values.

load. This facility had shown that both boilers, and generators had the potential to global warming based on CO₂ eq values.

3.5.3 Sheikhpura

Table 3.13: Total CO₂-eq (kg/m³) calculated for Sheikhpura beverage industry

Source	CO ₂ (%)	CO ₂ -eq (kg/m ³)
Boiler-1	8.4	0.1518
Boiler-2	6.5	0.1175
Generator-1	6.4	0.1157
Generator-2	5.5	0.0995
Generator-3	7.6	0.1374

The boilers had highest CO₂ concentrations and equivalent values followed by generators. Boiler 1 had the highest values followed by generator 3 at 8.4% and 0.15 kg per m³. The higher values are mainly due to continuous operation, higher fuel usage, and combustion for the heat generation, which is very common in beverage manufacturing for washing, heating, and bottling process. Boiler 2 and Generator 2 had shown lower impact compared to other boiler 1 and other generators, which can be due to better combustion efficiency, shorter operation time and overall lower load. This facility had shown that both boilers and generator had potential to cause global warming based on CO₂ eq values.

3.5.4 Haripur

Table 3.14: Total CO₂-eq (kg/m³) calculated for Haripur beverage industry

Source	CO ₂ (%)	CO ₂ -eq (kg/m ³)
Boiler-1	7.3	0.1318
Boiler-2	5.3	0.0958
Generator-1	5.9	0.1065
Generator-2	8.4	0.1518
Generator-3	9.1	0.1644

The generator had highest CO₂ concentrations and equivalent values followed by boilers. Generator 3 had the highest values followed by boiler 1 at 9.1% and 0.16 kg per m³. The higher values are mainly due to continuous operating time, maximum fuel usage, and more combustion for the heat generation, common in beverage manufacturing for

washing, heating, and bottling process. Boiler 2 and Generator 1 had shown lower impact compared to other boiler 1 and other generators (2 and 3), which can be due to better combustion efficiency, shorter operation time and overall lower load. This facility had shown that generator had the maximum potential to global warming based on CO₂ eq values.

3.5.5 Rawalpindi

Table 3.15: Total CO₂-eq (kg/m³) calculated for Rawalpindi beverage industry

Source	CO ₂ (%)	CO ₂ -eq (kg/m ³)
Boiler-1	9.4	0.1700
Boiler-2	7.6	0.1376
Generator-1	8.3	0.1506
Generator-2	8.1	0.1470
Generator-3	7.9	0.1434

The boilers and generators both had the highest CO₂ concentrations and equivalent values. Boiler 1 had the highest values followed by boiler 2 (9.4% and 0.17 kg per m³). Generator 1 had shown higher impact (8.3 CO₂ % and 0.15 kg per m³) close to generator 2 and 3, which can be due to higher combustion load, longer operation time and load conditions. This facility had shown that both boilers and generator had maximum potential to global warming contributing based on CO₂ eq values.

Akhtar et al. (2017) also found that stationary combustion sources like boilers and generators contribute to overall greenhouse gas emissions in carbon dioxide equivalent using IPCC and GHG protocol methods. He also found generators and boilers are key scope 1 emission sources similar to our study where boilers and generators contribute differently to total carbon dioxide equivalent levels (Akhtar et al., 2017). Mir et al. (2020) also highlighted that carbon dioxide CO₂ emissions remain the dominant greenhouse gases from fossil fuel combustions, reinforcing why CO₂ equivalent emissions result from boilers and generators are important indicators of industrial climate change (Mir et al., 2020). Mir et al. (2017) also found that industrial processes are significant contributor to greenhouse gases particularly CO₂ emissions alongside energy and agricultural sectors

indicating an increasing emission trend over time (Mir et al., 2017). Ning et al. (2022) found that found Faisalabad and Rawalpindi as major regions with significant industrial and economic activity similar to our results ranking highest in CO₂ emissions in the country reflecting impacts of anthropogenic activities and urban growth (Ning et al., 2022). Akhtar et al. (2025) reported high emissions of CO, Nox and SO₂ from different fuel types other than natural gas with had shown lowest emissions within limits in the textile industries of Faisalabad (Akhtar et al., 2025). The results of GWP in terms of C02 Eq suggested that emission control and mitigation efforts should prioritize boilers and generators in facility with more emissions improving efficiency and adopting cleaner fuels options such as natural gas, optimization of operations and cleaner technologies. The findings highlight the pressing necessity for the implementation of cleaner fuels, improved emission control systems, and more stringent regulatory enforcement to alleviate environmental and health repercussions in Pakistan's beverage industries.

CONCLUSION

1. The results of ambient air quality at five (05) beverage industries revealed that all assessed parameters were within the recommended limit given Pak NEQs. The noise levels were significantly higher but within the safe limit by WHO. Wind speed, direction, humidity and temperature were varied across all five industries.
2. The results of stack emissions revealed that Faisalabad's diesel-powered boilers and generators exceeded Pak NEQs, with boiler 1 emitting the most CO and SO₂, boiler 2, generator 2 and 3 had highest NO, NO_x, and PM, emissions under specified load settings. Lahore's Boiler 1 emitted higher CO, NO, NO_x, and PM above Pak NEQs (Boilers used natural gas). SO₂ and NO₂ met Pak NEQs. However, CO, SO₂, NO, NO_x, and PM from Generators 1 and 3 exceeded Pak NEQ standards (diesel-fueled, fully loaded). Rawalpindi also had natural gas boilers and diesel generators which had been fully loaded. SO₂ and NO₂ met Pak NEQs, but CO, NO, NO_x, and PM exceeded. Generators 2 and 3 emitted more CO and NO_x. The Haripur industry also had fully loaded natural gas boilers and diesel generators. CO₂ and NO₂ met Pak NEQs but CO, SO₂, NO, NO_x, PM were over limits. Generators had the highest CO and NO_x emissions. NO was higher in boiler 1 (167 ± 23.06) and generator 3 (190 ± 10.0). Overall emissions were low. In Sheikhpura industry, boiler 2 had higher emissions than boiler 1. CO (334.3 ± 30.2), SO₂, NO (423.0 ± 13.0), NO_x (458.0 ± 18.0), and PM (89.6 ± 0.1) exceeded Pak NEQs. At generator 3, diesel emissions were highest. CO, SO₂, NO, NO_x, PM exceeded limits; NO₂ and CO₂ were within. Both machines were fully loaded.
3. Comparative analysis revealed that boiler 1 in Lahore exceeded the safe PM level ($62.2 \mu\text{g}/\text{m}^3$), but boiler 2 was below the $35 \mu\text{g}/\text{m}^3$ guideline. Sheikhpura boiler 2 emitted high PM ($89.4 \mu\text{g}/\text{m}^3$). PM levels in Haripur and Rawalpindi boilers were safe. Uneven fuel combustion, poor fuel quality, and poor pollution management can generate boiler PM. All beverage boilers exceeded Pak NEQs' CO limits ($232.6 \mu\text{g}/\text{m}^3$). Incorrect fuel ratios and combustion temperatures increase CO emissions. Improper furnace and control system maintenance can increase emissions. Boilers in Faisalabad had higher SO₂ levels ($409.3 \mu\text{g}/\text{m}^3$). All boilers NO₂ emissions were acceptable. All generators went against Pak EPA PM emissions limits ($76.8 \mu\text{g}/\text{m}^3$). Diesel fuel

combustion with low air-fuel mixing ratios produces particulates. NO₂ emissions were safe. SO₂ levels of Lahore, Sheikhupura, and Faisalabad (161.6 µg/m³) exceeded Pak NEQs due to diesel generators. Haripur and Rawalpindi had safe SO₂ levels. Generators also exceeded CO (284.8 µg/m³) Pak NEQ emission limitations. CO emissions rise with poor diesel generator maintenance and control.

4. The calculations of global warming potential expressed in CO₂ equivalents indicated that Faisalabad and Rawalpindi exhibited the highest emission potentials, followed by Lahore, Haripur, and Sheikhupura. In general, boilers exhibited higher CO₂ percentages and equivalent values than generators. CO₂ percentages range from 9.47% to 9.57%, with equivalent values of 0.17 kg per m³.

RECOMMENDATIONS

Based on the findings of the present study, the following recommendations are specifically proposed for the **five beverage industries selected for this study**:

1. **Emission control:** The selected industries should improve the operation and maintenance of boilers and diesel generators, particularly where elevated concentrations of CO, SO₂, NO_x, and particulate matter were observed.
2. **Fuel management:** The selected industries should ensure proper fuel quality, fuel-to-air ratios, and combustion conditions to reduce incomplete combustion and associated emissions.
3. **Generator operation:** Diesel generators showing comparatively higher pollutant concentrations should undergo regular maintenance, tuning, and emission-performance checks.
4. **Boiler management:** The boilers at the selected facilities should be regularly inspected and maintained to improve combustion efficiency and minimize pollutant emissions.
5. **Air pollution control:** Where technically applicable, the selected industries should evaluate the need for appropriate emission-control systems based on the pollutant levels observed during this study.
6. **Continuous monitoring:** Periodic ambient air-quality and stack-emission monitoring should be conducted at the selected facilities to identify changes in emission levels and assess compliance with applicable environmental standards.
7. **Energy efficiency:** The selected industries should evaluate opportunities to improve energy efficiency and reduce unnecessary fuel consumption, thereby reducing associated greenhouse-gas emissions.
8. **Global warming potential:** The selected industries should maintain records of fuel consumption and relevant emission data to facilitate more accurate assessment and management of their greenhouse-gas emissions. must consider shifting to cleaner fuels such as natural gas for generators to reduce the emissions.

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