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Investigating the Impact of Shifting the Brick Kiln Industry from Conventional to Zigzag Technology for a Sustainable Environment

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Abstract: The brick kiln industry is one of the largest and most highly unregulated industrial sectors in developing countries. Most of the kilns use low-quality coal as primary fuel along with small quantities of bagasse, rice husk, and wooden chips. As a result of inefficient methods of combustion in conventional brick kilns, such as fixed chimney Bull's trench kilns (FCBTKs), harmful pollutants are emitted in high quantities, which ultimately deteriorate the environment and are widely in operation in Pakistan. The most prominent harmful pollutants include carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), black carbon (BC), and particulate matter less than 2.5 microns ($PM_{2.5}$). Over the years, new technologies have been adopted by developed countries for the reduction of environmental burdens. One of these technologies is induced draught zigzag kilns (IDZKs), or zigzag kilns (ZZKs), technology, which effectively improves the combustion across the path of bricks stacked in a zigzag pattern. For the mass adoption of this technology, environmental assessment and comparison of both technologies is a crucial step. Both types of kiln sites are investigated for the analysis of their emissions and their environmental impact in this work. Carbon mass balance equations are used for the calculation of emission factors. Collected inventory data is then used for the life cycle assessment of both types of kilns using open LCA (version 1.10.3) and the Eco-invent database. According to the study, ZZK technology outperforms FCBTK in all aspects. The analysis of the specific energy consumption (SEC) of fired bricks for each kiln type reveals that ZZKs require 30% less energy than the conventional FCBTK. This implies that ZZKs demand lesser fuel than FCBTKs. The zigzag technology adoption scenario, in particular, can lead to approximately 30% lower CO_2 emissions, which can be further reduced by up to 80% when taking into account black carbon (BC) emissions. Additionally, the adoption of zigzag technology can result in a 35% decrease in $PM_{2.5}$ emissions. The study shows that adopting ZZK technology significantly reduces impact categories, such as particulate matter formation (PMF), photochemical oxidant formation (POF), and terrestrial acidification (TA) by 63%, 93%, and 95%, respectively.

Keywords: brick kilns; greenhouse gases; specific energy consumption; terrestrial acidification; emission factors

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1. Introduction

Brick manufacturing can be dated back to 5000 B.C. as archaeologists found bricks in the Indus Valley civilization while digging for a railway track in the mid-19th century. Owing to their increasing population, third-world countries mostly rely on brick manufacturing through centuries-old technologies that contribute to environmental deterioration and adverse social impacts. According to the World Bricks and Blocks Market report published by Zion Market Research in January 2021, the global bricks market was valued at approximately USD 140.43 billion in 2019 and is expected to generate revenue of around USD 200.51 billion by the end of 2026, growing at a CAGR of around 5.8% between 2020 and 2026 [1]. According to the Brick Development Association (BDA), the UK brick industry produced around 1.9 billion bricks in 2020. The BDA represents the UK brick manufacturers and estimates that the industry produces around 2 billion bricks per year [2]. Overall, it is challenging to estimate the exact number of bricks produced worldwide per year as there is no centralized database tracking this information; however, based on the data provided by various sources, it is safe to assume that global brick production is in the billions. Brick kiln operation via old technology is as deadly a menace as coronavirus. With the increasing global warming and smog patterns during winters, there is a dire need to implement rigorous actions including shifting the traditional brick kilns to new and cleaner technologies [3].

According to a study done by Southern Africa Clay Brick Association (CBA), there are around 300,000 formal brick kilns globally that produce around 1500 billion bricks annually. The building sector shares 36% of global energy consumption and remains one of the largest contributors to greenhouse gas (GHG) emissions. On one hand, harmful emissions such as CO_x, NO_x, SO_x, and particulate matter ($PM_{2.5}$) degrade the environment as a whole, and on the other hand, it is damaging for the workers as well as the general population living in the vicinities of these brick kilns. This research did not include NO_x emissions this time. Moreover, the air quality index (AQI) across major cities of the country is mostly greater than environmental management agency (EMA) standards, i.e., >100 AQI. The global brick industry emits 2.7% of carbon emissions [4]. Overall, the major adverse impacts of brick production are related to human health, ecosystem quality, climate change, and resource depletion. The problem can be reduced significantly by using more efficient and clean technologies, mainly zigzag technology, and using cleaner fuels, such as paper sludge and biomass instead of coal [5].

The environment has deteriorated since industrialization driven by rising demands for goods due to the population explosion. The world population is estimated to be around 8 billion as of November 2022 [6]. To cover the needs of such a great number of end users, the demand for transportation, power generation, and manufacturing is on the rise. Out of these sectors, the brick sector is the one contributing the highest amount of pollution to air [7,8]. Most of these brick kilns operating in developing countries are unregulated and no checks are in place to minimize the emissions with optimizations of conventional technologies [9,10]. There are more than 20,000 brick kilns in Pakistan, mostly in Punjab. Around 20–30% of national coal consumption is related to this sector [11,12].

The research and development of more effective and ecologically responsible brick kiln technologies has attracted increasing attention in recent years. Some of the technologies that have been created include zigzag kilns, modified Hoffman kilns, and vertical shaft brick kilns (VSBKs) [13]. One of the most ecologically benign and energy-efficient brick kiln systems is the VSBK. Because of their vertical shaft construction, heat and combustion fumes can be distributed more evenly. As a result, fuel is used more effectively, and there are fewer releases of pollutants [14]. To evaluate the effects of VSBKs on the ecosystem, several LCAs have been carried out. For instance, research in India examined the effects of conventional brick kilns and VSBKs on the environment [15]. According to the findings, VSBKs emit fewer greenhouse gases and other contaminants, such as particle matter and nitrogen oxides, than conventional brick kilns.

Another innovation to lessen the negative effects of brick kilns on the atmosphere is the hybrid Hoffman kiln (HHK). To produce a brick kiln that is more effective and ecologically friendly, HHKs incorporate components from both conventional Hoffman kilns and VSBKs. For instance, research in China [16] contrasted the effects of HHKs and conventional brick kilns on the environment. The findings demonstrated that compared to conventional brick kilns, HHKs had reduced releases of toxins and greenhouse gases, such as sulfur dioxide and particulate matter. The zigzag kiln is yet another advancement in brick kiln environmental effect mitigation technology. Zigzag kilns route combustion gases through the brick stack in a zigzag design, which results in more effective fuel use and fewer pollution releases [17]. According to the findings, zigzag brick kilns emit less carbon monoxide and particle matter than conventional brick kilns.

FCBTKs are a widely used technology across the country, having many drawbacks in terms of energy efficiency and higher emissions, whereas ZZKs have fewer emissions, better heat transfer characteristics, and greater efficiency due to optimized airflow [18]. More developed countries have opted for even more efficient technologies [19], such as VSBKs and tunnel kilns [20]. To cater to this gloomy state of affairs, NEECA, BKOAP, and ICIMOD have developed a roadmap to replace conventional brick kilns with modern technology [21,22]. Retrofitting conventional FCBTKs is quite easy, and no excessive capital cost is involved in it.

Converting conventional kilns to zigzag kiln technology can have significant economic benefits, primarily through cost savings on fuel and increased productivity. Zigzag kilns are more energy-efficient than conventional kilns, resulting in significant cost savings on fuel. For example, a study by the United Nations Development Program (UNDP) found that a zigzag kiln in Nepal reduced fuel consumption by 35% compared to a traditional fixed chimney kiln. Similarly, a study by the International Centre for Integrated Mountain Development (ICIMOD) found that zigzag kilns in Bhutan reduced fuel consumption by up to 30%. These energy savings can result in substantial cost savings for kiln operators, particularly in areas where fuel costs are high. Zigzag kilns are designed to burn fuel more efficiently and reduce emissions of pollutants, such as particulate matter and carbon monoxide. This can result in environmental benefits, such as improved air quality, and potentially avoiding or reducing the cost of compliance with emissions regulations. For example, a study by the IFC found that zigzag kilns in Bangladesh reduced particulate matter emissions by 45–50% and carbon monoxide emissions by 60–80% compared to conventional kilns. This could help kiln operators avoid fines or penalties for non-compliance with emissions regulations and potentially qualify for carbon credits or other incentives [23].

The world is on the verge of destruction due to emissions caused by burning fossil fuels. Anthropogenic activities and overdependence on fossil fuels has made the situation even worse. Each harmful emission emitted from various activities contributes differently and aggravates environmental deterioration. One of the main reasons for global warming is CO_2, causing global temperature rise, changes in weather and severe flooding [19]. Besides CO_2, another harmful gas emitted from burning coal in brick kilns is carbon monoxide (CO), which is a precursor to cardiovascular problems and increases mortality rates [24]. Freshwater acidification and smog are caused by SO_2 [25]. Though BC emissions are minute, these are contributing to climatic disruptions [26]. NO_x is mainly produced by human activities as an adverse product that is depleting the ozone layer [27]. Even small quantities of CH_4 have the potential to cause a bigger greenhouse effect [28]. Other than these emissions, NMVOCs and methane are precursors for ground-level ozone formation [29]. The damaging effects of these emissions call for a holistic approach to cutting down fossil fuels and adopting modern efficient techniques.

Life cycle assessment (LCA) is an efficient tool to analyze the environmental impacts, inputs, and outputs of different products during their life cycle [30]. Moreover, LCA serves as an effective method when comparing conventional technologies with modern ones [31] and can be considered from the product design and development phase [32]. LCA is a multifaceted tool used to conduct studies in different areas and industrial infrastructures [33]. Regarding the LCA study of brick kilns, the first study on the LCA of bricks was conducted in 2007 [34]. Since then, several studies have been conducted each year on the life cycle of bricks and their production technologies. Regarding software for the LCA, SimaPro has been widely employed; however, openLCA has been used since 2016 and is becoming a popular software among practitioners [35]. Throughout their life cycle, brick kilns need non-renewable raw materials, high temperatures for the production phase, and enormous amounts of energy as inputs [36]. As a result of combustion, greenhouse gases emitted from their chimneys serve as outputs [37].

The goal of this work is to provide a thorough, scientifically grounded, and unbiased evaluation of the brick kiln industry by assessing the long-term negative effects of emissions produced by conventional brick kilns as compared to ZZKs. Since the brick kiln industry is one of the least sustainable sectors of the economy, the topic is distinctive because it has not been covered in any prior research. Additionally, it will assist the government in properly regulating the industry. The research objectives of this research range from data collection to presenting the LCA results. Firstly, a comprehensive assessment of the long-term fuel and energy savings potential of ZZKs. Secondly, GHG mitigations of ZZKs are appraised and quantified for the reduction of pollutant emissions due to phasing out conventional kilns. Lastly, a comparison is established between the environmental impact of ZZKs and FCBTKs using the openLCA tool.

2. Methodology

The Punjab province of Pakistan is well known for its agricultural products, mainly due to good quality soil. This soil usually requires less quantity of coal to be burnt during the baking process. Around 20,000 brick kilns are operating in Punjab, which are consuming about 2.85 million tons of coal. Additionally, other types of fuel, such as sawdust, bagasse, and rice husk, are also utilized by these kilns. To initiate the LCA of brick kilns, site visits were conducted for quantitative and qualitative data collection. These data include energy and material consumption, heat loss, and emissions and are presented in Tables 1 and 2. The LCA model consists of inventory data on energy and material consumption and emissions from brick kilns. OpenLCA 1.10.3 is used for the life cycle assessment of both technologies. Data are collected for both traditional as well as zigzag kilns to compare both technologies in terms of environmental impacts.

Table 1. Input inventory data for FCBTKs and ZZKs.

Material	Quantity	
	FCBTKs	ZZKs
Soil	3000 kg	3000 kg
Water	1 m^3	1 m^3
Sand	50 kg	50 kg
Coal	275 kg	220 kg
Electricity	10 kWh	10 kWh

Table 2. Output inventory data for FCBTKs and ZZKs.

Pollutant	Quantity (g/kg of Fuel)	
	FCBTKs	ZZKs
CO	6600	3036
CO_2	448,250	310,200
SO_2	3905	250.8
$PM_{2.5}$	1485	770
Carbon Black	101.7	13.2

Four to six hours of sampling time was taken into consideration for data gathering. Due to kilns undergoing continual operation, baking bricks is a continuous process. Other tasks, however, such as loading green bricks, unloading red bricks, crushing coal, molding, etc., are only done during the day. We divided all kilns into two types based on our conversations with internal scientists, BKOAP officials, and brick industry professionals in this area, i.e., traditional fixed chimney force draught zigzag kiln and fixed chimney straight line Bull's trench. Around 20,000 brick kilns are operating fixed chimney straight line Bull's trench kiln, and one recently introduced forced draught zigzag kiln was chosen.

First of all, site investigations for tracing and documenting brick production supported by data from the literature are conducted. Secondly, inventory data for ZZKs and FCBTKs are collected through site visits and the literature. All data, including inputs and outputs for the life cycle of brick production, are either provided by the company under study or the Eco-invent database. Moreover, data are acquired through personal interviews with brick kiln owners. Finally, the emission factors of the pollutants are calculated and incorporated in openLCA to compare the environmental impact of both technologies in terms of different impact categories. A methodological framework is presented in Figure 1.

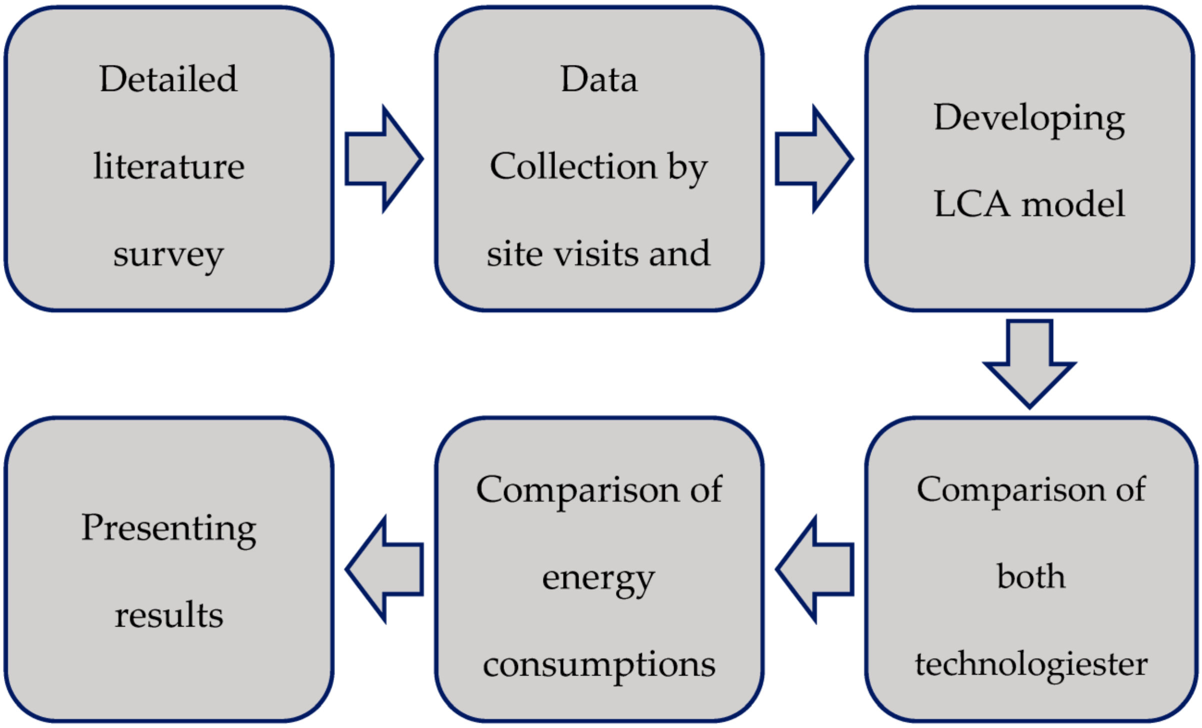

Figure 1. The methodological framework of this work.

Two different brick kiln sites, one FCBTK, and the other ZZK, are monitored for the same inputs such as soil, water, sand, coal, and electricity for the production of 1000 bricks from each kiln. The 3000 kg soil is used as the primary raw material for making bricks. Then, 1 cm^3 of water is added to the soil to create the desired consistency for molding the bricks. Sometimes, 50 kg sand is added to the soil–water mixture to improve the texture and strength of the bricks. A total of 275 kg coal is used as the primary source of fuel to fire the bricks in the kiln. It provides the necessary heat to transform the raw materials into finished bricks. Additionally, 10 kWh of electricity may be used to power equipment and machinery in the brick-making process, such as mixing machines, crushers, and conveyor belts.

To determine the specific energy consumption (SEC) of fired bricks for different kiln types, the amount of fuel charged per shovel and the total number of shovels used are multiplied together. While coal is the main fuel used in brick kilns, some other fuels such as bagasse, sawdust, and rice husk are also used. The data for emission analysis are gathered by visiting one ZZK and one FCBTK in Punjab. Ratnoze was used to measure the real-time concentrations of gaseous and particle contaminants, while filter samples were collected to determine the gravimetric $PM_{2.5}$ mass. The carbon mass balance approach was employed to calculate the emission factors (EF) for various pollutants, including CO_2, CO, SO_2, $PM_{2.5}$, and BC, based on real-time pollutant concentrations from Ratnam. To determine the emission factors for each pollutant, the carbon mass balance method was used. The Ratnam Oxide Sampler is a portable device that measures real-time concentrations of various gases and particulate matter (PM) in industrial emissions. It consists of a sampling probe that is inserted into the flue gas duct, a filter to remove particulate matter, and a gas analyzer to measure the concentrations of various pollutants. The device can measure a range of emissions, including carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter ($PM_{2.5}$ and PM_{10}). The Ratnam device works by extracting a sample of the flue gas and directing it through the filter, which collects particulate matter. The gas then flows through a series of sensors that measure the concentrations of various pollutants. The real-time data is displayed on a screen, allowing operators to monitor and adjust emissions in real-time. The Ratnam device is widely used in the industrial sector to monitor emissions from various sources, including kilns, boilers, and furnaces. Approximately 6600 g of CO was released per kilogram of fuel burned in the FCBTKs, and 448,250 g of CO_2 was released per kilogram of fuel burned in the FCBTKs. SO_2, $PM_{2.5}$, and black carbon were measured at 2905, 1485, and 101.7 g per kilogram of fuel used. The emissions from the ZZKs were measured as follows: for every kilogram of fuel used; 3036 g of CO; 310,200 g of CO_2; 250.8 g of SO_2; 770 g of $PM_{2.5}$; and 13.2 g of black carbon were emitted.

Some assumptions are used to produce projections in the detailed bottom-up model. The brick kiln business employs coals of varying quality, ranging from sub-bituminous coal to different types of lignite. It has been assumed that fuel has a calorific value of 18.8 MJ/kg. The weight and dimensions of bricks being made vary significantly. Calculations for the most prevalent type have been done for this investigation, which is a 3 kg brick with dimensions 228 mm × 101 mm × 76 mm. It is assumed that 1000 bricks are produced employing each of the technologies to compare the emissions and impact categories of the LCA. In the LCA study, there are different approaches such as cradle-to-grave, cradle-to-gate, and gate-to-gate. The gate-to-gate approach is used in this research.

3. Results and Discussion

3.1. Analysis of Specific Energy Consumption

For the specific energy consumption (SEC) of fired bricks for each type of kiln, a product of one shovel of charged fuel and a total number of charged shovels is calculated. Since, the primary source of fuel used in the brick kiln industry is coal, a fraction of other fuels such as bagasse, sawdust, and rice husk are also consumed. It was observed that about 40% of a reduction in SEC is achieved by converting from FCBTK to ZZK.

After the ultimate/proximate analysis of fuel samples, one can calculate the *SEC*. Let '*a*' be the average mass of bricks in kg, '*b*' be the total number of bricks, and '*y*' be the mass of coal in kg, and '*CV*' denote the calorific value of coal in kCal. The following relation (Equation (1)) can be used to evaluate the *SEC* of a kiln:

$$SEC = \frac{y \times CV \times 4.18 \times 1000}{a \times b} \text{ (MJ/kg of fired bricks)} \quad (1)$$

3.1.1. Specific Energy Consumption in Fixed Chimney Bull's Trench Kilns

Several factors affect the SEC in FCBTKs, including the quality and quantity of coal used, the moisture content of the clay, the size and shape of the bricks, the firing temperature, and the kiln design. Therefore, the analysis of the SEC in FCBTKs requires a comprehensive understanding of these factors.

The first step in analyzing the SEC in FCBTKs is to measure the energy input and output of the kiln. The energy input includes the energy required to dry the green bricks, the energy required to fire the bricks, and the energy lost due to heat transfer and radiation. The energy output is the energy contained in the fired bricks. The difference between the energy input and output is the energy lost during the process.

The SEC can be calculated by dividing the total energy input by the total product output. This can be expressed as SEC = (energy input/product output). The product output is usually measured in terms of the number or weight of bricks produced.

To reduce the SEC in FCBTKs, several measures can be taken, such as using high-quality coal, reducing the moisture content of the clay, optimizing the size and shape of the bricks, increasing the firing temperature, and improving the kiln design. These measures can help to increase the energy efficiency of the kiln and reduce the energy lost during the process. In addition to reducing the SEC, improving the energy efficiency of FCBTKs has several other benefits, including reducing greenhouse gas emissions, improving the quality of the fired bricks, and reducing the health risks associated with traditional brick-making practices.

3.1.2. Specific Energy Consumption in Zigzag Kilns

Zigzag brick kilns are designed with a zigzag pattern in the firing zone, which helps to reduce heat loss and increase heat transfer efficiency. The fuel is fed into the kiln from one end and the flue gases exit from the other end, passing through a series of baffles that force the gases to flow in a zigzag pattern. This design helps to increase the residence time of the flue gases in the kiln, allowing them to transfer more heat to the bricks.

One of the key advantages of zigzag brick kilns is that they can use a variety of fuels, including coal, biomass, and even agricultural waste, such as rice husk and wheat straw. However, the quality of the fuel used can have a significant impact on the SEC. Low-quality fuels, such as biomass and agricultural waste tend to have lower energy density and higher moisture content, which can lead to a higher SEC. Therefore, it is important to use high-quality fuels and ensure that they are properly dried before use. The reduction in specific energy consumption depends on various factors, such as the type of fuel used, the size of the kiln, and the initial energy efficiency of the kiln.

3.2. Emission Analysis

Emission analysis is a critical component of the environmental impact study of brick kilns. The brick kiln industry has been identified as a significant source of air pollution, with emissions of particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, and other pollutants. These emissions can have a range of impacts on the environment and human health, including climate change, acid rain, respiratory diseases, and other health effects. Therefore, understanding and analyzing the emissions from brick kilns is crucial for identifying the environmental impacts of the kilns and developing strategies for mitigating these impacts.

The data for emission analysis was collected with the collaboration of NEECA and ICIMOD by visiting one ZZK and one FCBTK kiln in Punjab. Real-time concentrations of gaseous and particle contaminants were measured using Ratnoze. To determine the gravimetric $PM_{2.5}$ mass, filter samples were gathered. The carbon mass balance approach was utilized to determine the emission factors (EF) for CO_2, CO, SO_2, $PM_{2.5}$, and BC using real-time pollutant concentrations from Ratnoze. Calculations of emission factors for each pollutant was carried out using the carbon mass balance method and the calculations [20] given below:

$$C_j = C_j^* \times DLR \, \frac{P \times 12}{T \times R}$$

$$Total\ Carbon = C_{CO2} + C_{CO} + C_{PM} + C_{VOC}$$

$$CO_2\ Emission\ Factor = \frac{C\ Fuel \times C_{CO2} \times \frac{44}{12} \times 1000}{Total\ Carbon}$$

$$CO\ Emission\ Factor = \frac{C\ Fuel \times C_{CO} \times \frac{28}{12} \times 1000}{Total\ Carbon}$$

$$PM_{2.5}\ Emission\ Factor = \frac{C\ Fuel \times PM_{2.5} \times 1000}{Total\ Carbon}$$

$$SO_2\ Emission\ Factor = CO\ Emission\ Factor \times \frac{SO_2(ppm)}{CO(ppm)} \times \frac{64}{28}$$

Here, C_j is the carbon mass concentration of species j in $\mu g_c m^3$,

C_j^* is the gaseous species j concentration after dilution in ppm,

DLR is the ratio of dilution. P, T, and R are pressure, temperature, and ideal gas constant, respectively, and *C Fuel* is the carbon fraction in fuel. A summary of the emission factors for FCBTK and ZZK kilns is given in Table 3.

Table 3. Summary of emission factors.

Pollutant	Kiln Type	
	FCBTK	**ZZK**
CO (g/kg)	24	13.8
CO_2 (g/kg)	1630	1410
SO_2 (g/kg)	14.2	1.14
$PM_{2.5}$ (g/kg)	5.4	3.5
BC (g/kg)	0.37	0.06

3.2.1. Reduction in CO Emissions through Retrofitting Measures

Conventional brick kilns are a major source of air pollution, emitting large amounts of carbon monoxide (CO), particulate matter, and other pollutants. These emissions have significant environmental and health impacts, contributing to climate change and causing respiratory illnesses in nearby communities. Retrofitting these kilns with zigzag technology is a promising approach to reducing CO emissions and improving air quality. CO is a colourless, odourless gas that is formed during the incomplete combustion of fuels. In brick kilns, CO is generated as a result of incomplete combustion of coal or other solid fuels. CO emissions from brick kilns can be reduced by improving the combustion efficiency of the fuel, which can be achieved by retrofitting the kiln with zigzag technology.

The zigzag kiln design has several features that promote more complete combustion and reduce CO emissions. First, the zigzag airflow pattern ensures that the hot flue gases are in contact with the bricks for a longer period, which promotes more complete combustion of the fuel. This reduces the amount of unburned fuel and the resulting CO emissions. Second, the zigzag kiln design provides better control of the combustion air, allowing for more precise regulation of the air-to-fuel ratio. This can be important because excess air can result in incomplete combustion and increased CO emissions, while insufficient air can lead to incomplete combustion and increased particulate matter emissions. The zigzag kiln design allows for more precise control of the air-to-fuel ratio, which can result in more complete combustion and reduced CO emissions. Third, the zigzag kiln design has a longer firing zone than traditional kilns, which allows for more complete combustion of the fuel. This longer firing zone ensures that the bricks are exposed to high temperatures for a longer period, which promotes more complete combustion and reduces CO emissions.

International Centre for Integrated Mountain Development (ICIMOD) in Nepal found that retrofitting brick kilns with zigzag technology resulted in a reduction in CO emissions of around 40%. The study also found that the retrofitting reduced particulate matter emissions and improved the thermal efficiency of the kilns.

In addition to reducing CO emissions, retrofitting brick kilns with zigzag technology can have other environmental and economic benefits. For example, improved combustion efficiency can result in reduced fuel consumption and lower costs for kiln operators. This can help to make the brick-making process more sustainable and economically viable.

3.2.2. Reduction in CO_2 Emissions

Coal is one of the primary fuels used in conventional brick kilns, and its combustion releases large amounts of carbon dioxide (CO_2) into the atmosphere. The use of coal in brick-making contributes to climate change and its associated impacts, such as rising temperatures and more frequent extreme weather events. Retrofitting brick kilns with zigzag technology is a promising approach to reducing CO_2 emissions and mitigating the environmental impacts of brick-making.

Zigzag technology can reduce CO_2 emissions in several ways. First, it can improve the combustion efficiency of coal, resulting in a more complete burn and reduced emissions. Second, it can reduce the amount of coal required to produce a given quantity of bricks, thereby reducing emissions from the coal production and transportation supply chain. Finally, it can increase the thermal efficiency of the kiln, which can reduce the overall energy consumption and emissions associated with the brickmaking process.

Reducing the amount of coal required to produce a given quantity of bricks is another way that zigzag technology can reduce CO_2 emissions. By improving the combustion efficiency of coal, zigzag technology can reduce the amount of coal required to produce a given quantity of bricks. This reduces the emissions associated with the production and transportation of coal, as well as the emissions associated with the combustion of coal in the kiln. Increasing the thermal efficiency of the kiln is another way that zigzag technology can reduce CO_2 emissions. Thermal efficiency refers to the percentage of heat generated by the kiln that is used to heat the bricks. In conventional brick kilns, thermal efficiency is often low due to factors such as poor insulation, poor airflow, and inadequate control of combustion parameters. Zigzag technology can address these issues by improving insulation, optimizing airflow, and providing better control of combustion parameters.

By improving the thermal efficiency of the kiln, zigzag technology can reduce the overall energy consumption and emissions associated with the brick-making process. This is because less energy is required to heat the kiln and produce the bricks, which reduces the amount of coal required and the associated emissions.

Studies have shown that retrofitting brick kilns with zigzag technology can result in significant reductions in CO_2 emissions. For example, a study conducted by the United Nations Development Programme (UNDP) in Nepal found that the specific CO_2 emissions of a traditional brick kiln were around 1150 kg CO_2/ton of fired bricks, while the specific CO_2 emissions of a zigzag kiln were around 720 kg CO_2/ton of fired bricks. This represents a reduction of around 37%.

3.2.3. Reduced Sulfur Dioxide Emissions

Sulfur dioxide (SO_2) emissions are a significant environmental concern associated with the use of conventional fixed chimney Bull's trench kilns (FCBTK) for brick production. FCBTKs are widely used in many parts of the world, including South Asia, and they are known to emit high levels of SO_2 and other pollutants. Retrofitting FCBTKs with modern zigzag brick kiln technology is one way to reduce SO_2 emissions and improve the environmental performance of the brick-making industry as presented in Table 4.

SO_2 is released during the combustion of coal in FCBTKs. Coal typically contains sulfur, and when it is burnt in the kiln, the sulfur is converted to SO_2 and released into the atmosphere. This is a significant environmental concern because SO_2 is a major contributor to air pollution and acid rain. SO_2 can also have adverse health effects on humans and animals, including respiratory problems, heart disease, and lung cancer.

In zigzag kilns, the air is forced to flow through the kiln in a zigzag pattern, allowing for more uniform heating and more complete combustion. This promotes a more complete burn of the coal, which reduces the amount of SO_2 and other pollutants that are released into the atmosphere. The zigzag pattern also provides better control of the air-to-fuel ratio, which is critical for optimizing combustion efficiency and reducing emissions. Reducing the amount of coal required to produce a given quantity of bricks and increasing the thermal efficiency of the kiln are other ways to reduce SO_2 emissions.

Table 4. Emissions concentrations in the case of FCBTKs and IDZKs.

Kiln Type	FCBTK	IDZK
Subcategory	Straight line	Induced draught zigzag
CO (ppm)	2349	718
CO_2 (ppm)	85,500	44,420
SO_2 (ppm)	648	27

3.2.4. Reduced $PM_{2.5}$ Emissions

Conventional fixed chimney Bull's trench kilns (FCBTKs) are known to emit significant amounts of air pollutants, including particulate matter less than 2.5 microns ($PM_{2.5}$), which has severe health and environmental impacts. As a result, there is a growing need to retrofit FCBTKs with modern technologies that can reduce $PM_{2.5}$ emissions and improve overall environmental performance. On the other hand, modern zigzag brick kiln technology (ZBTK) is an improved design that has shown promise in reducing $PM_{2.5}$ emissions from brick kilns. The retrofitting of FCBTKs with ZBTK technology involves several modifications that aim to improve combustion efficiency, reduce fuel consumption, and reduce emissions.

One of the many modifications in retrofitting FCBTKs with ZBTK technology is to replace the fixed chimney with a zigzag-shaped chimney which creates a longer and more turbulent path for exhaust gases and it reduces the height of the chimney and the overall energy requirements of the kiln, resulting in lower fuel consumption and emissions Table 5). Another key modification is the installation of an air duct system to preheat the combustion air to reduce the energy required for combustion, leading to lower fuel consumption and emissions. The preheating system also helps to maintain a consistent temperature in the kiln, improving combustion efficiency and reducing emissions. A forced air ventilation system is another crucial modification in retrofitting FCBTKs with ZBTK technology. The ventilation system increases the oxygen supply to the kiln, improving combustion efficiency and reducing emissions.

3.2.5. Reduction in Black Carbon Emissions

Black carbon, also known as soot, is a fine particulate matter that is produced from incomplete combustion of fossil fuels, biomass, and organic matter. It is a significant contributor to global warming and has adverse impacts on human health, the environment, and climate change. In South Asia, the brick kiln industry is one of the largest emitters of black carbon. The conventional fixed chimney bull's trench kilns (FCBTKs) used in the brick kiln industry are highly polluting and inefficient.

Retrofitting FCBTKs with ZVBKs can significantly reduce black carbon emissions. The zigzag design of the ZVBK allows for better combustion of the fuel, resulting in fewer emissions of black carbon and other pollutants as presented in Table 5. The piles of bricks move through the kiln in a zigzag pattern, which exposes them to hot gases for a longer period, allowing for almost a complete combustion. The recirculation system in the ZVBK allows for the reuse of hot air, reducing the amount of fuel needed to fire the bricks. This, in turn, reduces the amount of black carbon and other pollutants emitted from the kiln. The ZVBK provides more consistent firing conditions than FCBTKs, resulting in better-quality bricks with fewer defects. This means that fewer bricks will need to be discarded, reducing the amount of waste produced by the kiln. The improved combustion and recirculation system of the ZVBK result in reduced fuel consumption, which leads to lower emissions of black carbon and other pollutants.

Table 5. Particulate matter and black carbon concentrations for FCBTKs and ZZKs.

Kiln	FCBTK	ZZK
$PM_{2.5}$ (μg/m^3)	509,181	172,302
Black Carbon (μg/m^3)	48,698	3227

3.3. Analysis of Impact Categories

To understand the potential and magnitude of environmental burdens of any product or system, a life cycle impact assessment is used. The data for inputs and outputs for the brick-making process was collected from two different brick kiln sites. The first one was operating via old FCBTK technology, while the other one was retrofitted to a ZZK. Emission factors for CO, CO_2, SO_2, $PM_{2.5}$, and BC were calculated using the carbon mass balance method. Inputs consist of soil, sand, water, energy usage, and land occupied, and the outputs are all the pollutant emissions from the brick roasting phase. For life cycle inventory, the openLCA and eco-invent databases were used. To analyze and interpret the results in terms of different impact categories, such as terrestrial acidification, photochemical oxidant formation, and particulate matter formation, the recipe midpoint hierarchal method (2016) was used. The primary objective of the recipe method is to transform the long list of life cycle inventory, consequently resulting in a limited number of indicator scores. The life cycle inventory data for FCBTKs and ZZKs are listed in Tables 1 and 2, previously.

There are several impact categories in the recipe midpoint (H) method, such as global warming, terrestrial acidification, particulate matter formation, human toxicity, freshwater acidification, photochemical oxidant formation, and climate change. The most relevant categories in the brick roasting process are terrestrial acidification, photochemical oxidant formation, and particulate matter formation. The comparisons of FCBTKs and ZZKs in terms of different categories are presented in Figures 2–4.

3.3.1. Particulate Matter Formation

Particulate matter (PM) is a major air pollutant that has a significant impact on human health, the environment, and climate change. The PM formation life cycle impact category is a measure of the environmental impact of particulate matter emissions throughout their entire life cycle. This includes the production of raw materials, manufacturing, use, and disposal. The impact category is usually measured in terms of human health, ecosystem quality, and climate change.

The life cycle impact category of PM formation in ZZKs is lower than that of FCBTKs as presented in Figure 2. The design of the kiln allows for better combustion and recirculation of the hot air, which reduces the amount of fuel needed to fire the bricks. This, in turn, reduces the emission of particulate matter and other pollutants. The manufacturing and use of ZZKs also have a lower impact on the environment and human health than FCBTKs. The disposal of the kilns at the end of their life cycle can also have a lower impact on the environment than FCBTKs.

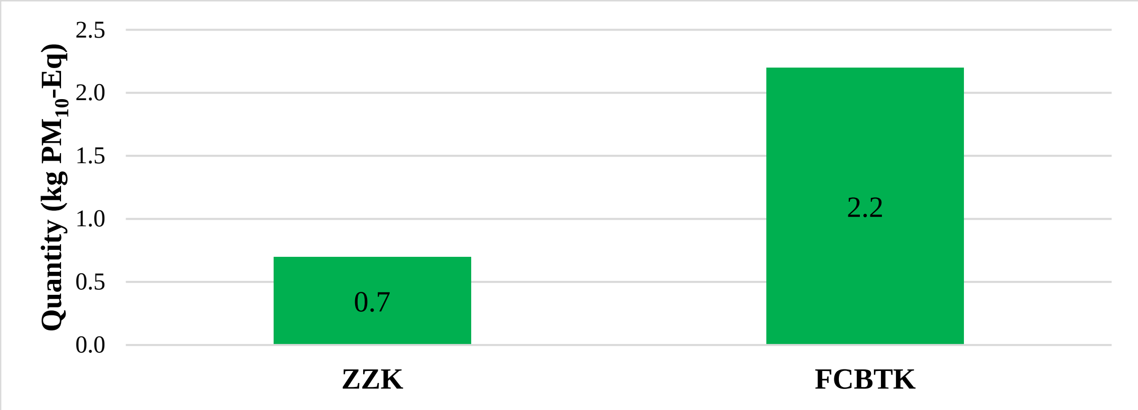

Figure 2. Comparison of particulate matter ($PM_{2.5}$) formation for fixed chimney Bull's trench kilns (FCBTKs) and zigzag kilns (ZZKs).

In general, the life cycle impact category of PM formation is higher in FCBTKs than ZZKs. This is because FCBTKs are less efficient and more polluting than ZZKs. The use of coal and other solid fuels in FCBTKs contributes to the depletion of natural resources and the emission of greenhouse gases.

3.3.2. Photochemical Oxidant Formation

Photochemical oxidants are air pollutants that are formed as a result of the reaction between VOCs and NOx in the presence of sunlight. These pollutants have a significant impact on human health, the environment, and climate change. The life cycle impact category of photochemical oxidant formation is lower in ZZKs compared to FCBTKs (Figure 3). This is primarily due to the design of the kiln, which allows for better combustion and recirculation of hot air, resulting in lower emissions of VOCs and NOx, which are the precursors of photochemical oxidants. Additionally, the use of modern technology in ZZKs, such as natural gas burners and automatic control systems, further reduces the emission of pollutants.

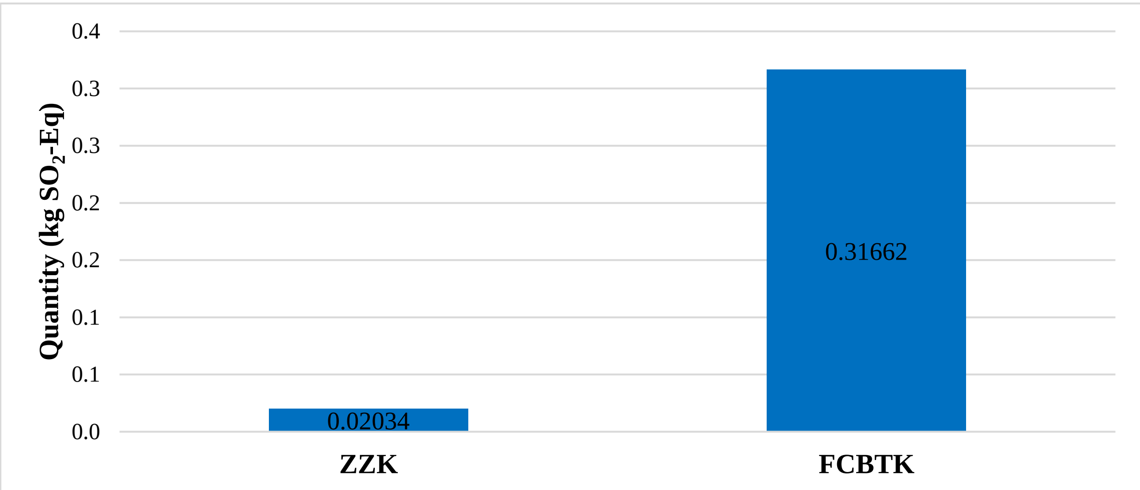

Figure 3. Comparison of photochemical oxidant for fixed chimney Bull's trench kilns (FCBTKs) and zigzag kilns (ZZKs).

Furthermore, the manufacturing and use of ZZKs also have a lower impact on the environment and human health than FCBTKs. For instance, the reduced fuel consumption in ZZKs reduces the carbon footprint and saves natural resources. Additionally, the emission of pollutants from ZZKs is lower, reducing the risk of respiratory diseases, acid rain, and ozone depletion. Moreover, the use of ZZKs has been shown to increase the durability and quality of the bricks, leading to fewer repairs and replacements.

3.3.3. Terrestrial Acidification

Terrestrial acidification is an environmental impact category that is used to measure the potential for a process or product to contribute to the acidification of soil and water. Acidification is a major environmental concern because it can lead to a decrease in soil fertility, loss of biodiversity, and damage to aquatic ecosystems. The importance of considering terrestrial acidification in the LCA study of brick kilns lies in its adverse effects on soil fertility, crop yields, and biodiversity. Acidification of the soil can lead to the leaching of essential nutrients such as calcium, magnesium, and potassium, making them unavailable for plant growth. This can lead to reduced crop yields and increased fertilizer requirements, leading to higher environmental impacts associated with the production and use of fertilizers. Additionally, acidic soils can harm beneficial microorganisms such as nitrogen-fixing bacteria, which can further reduce soil fertility. Therefore, identifying opportunities to reduce the emissions of NOx and SO_2 from brick kilns can help mitigate the environmental impact of brick manufacturing and improve soil quality.

When comparing the terrestrial acidification impact of the FCBTK and the zigzag kiln, it is clear that the ZZK is the more environmentally friendly option as can be seen in Figure 4. The FCBTK produces a larger amount of air pollution, solid waste, and carbon emissions than the ZZK, all of which can contribute to soil and water acidification. The ZZK, on the other hand, produces less of these pollutants, which reduces its potential impact on terrestrial acidification. In addition, the ZZK has a higher energy efficiency than the FCBTK, which means that less fuel is required to produce the same number of bricks. This reduces the carbon footprint of the kiln and contributes to the overall sustainability of the brick-making industry.

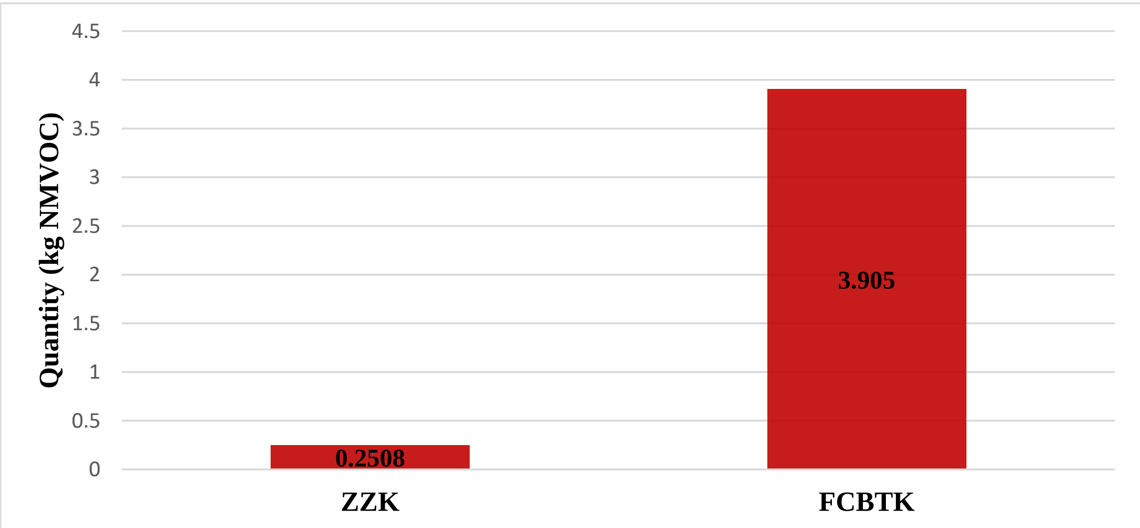

Figure 4. Terrestrial acidification for fixed chimney Bull's trench kilns (FCBTK) and zigzag kilns (ZZK).

The terrestrial acidification impact of the FCBTK and the ZZK is significantly different. The FCBTK produces a larger amount of air pollution, solid waste, and carbon emissions than the ZZK, which can contribute to soil and water acidification. The ZZK, on the other hand, has a higher energy efficiency, produces less air pollution and solid waste, and has a lower carbon footprint than the FCBTK.

These environmental impact categories demonstrate how effective and eco-friendly modern ZZK technology is. Particulate matter formation has been of much concern due to the deteriorating air quality index that employing ZZK technology has to correct, with a potential 30% less particulate formation with the use of ZZKs which is equivalent to 0.7 kg PM_{10}, while FCBTKs have a much higher value equivalent to 2.2 kg PM_{10}. The next most relevant impact category is found to be the photochemical oxidant formation, which is only 0.02 kg NMVOC when employing ZZKs as compared to 0.31 when employing FCBTKs. In the case of FCBTKs, terrestrial acidification is mostly driven by SO_2 concentrations in the atmosphere. In this comparative study, the difference between both technologies is much higher, where conventional FCBTK contributes equivalent to 3.9 kg of SO_2 and modern ZZK has only an impact equivalent to 0.25 kg of SO_2.

4. Conclusions

The LCA is a technique used to analyze the environmental effects of a product or process during its life cycle. In this context, an LCA study of zigzag kilns and fixed chimney Bull's trench kilns can provide insights into the environmental impacts associated with brick manufacturing. ZZK technology is better than FCBTKs in all aspects of the study. The SEC of fired bricks for each type of kiln shows that ZZKs have 30% less energy demand than conventional FCBTKs. Consequently, less fuel is required for ZZKs. The overall emissions performance of the monitored zigzag kilns was better than that of the monitored FCBTKs in this study. Adopting cleaner kiln technologies offer significant GHG reduction potential as the zigzag adoption scenario achieves about 30% lesser CO_2 emissions, 80% when considering BC emissions, and 35% when considering $PM_{2.5}$ emissions. The most relevant impact categories were found to be POF, PMF, and TA. The study suggests that PMF, POF, and TA are 63%, 93%, and 95% lower in the ZZK, respectively. Possible applications of the LCA study of zigzag kilns and fixed chimney Bull's trench kilns include the identification of opportunities for process improvement, such as energy and material efficiency, waste reduction, and emissions reduction. This study can help identify the most environmentally friendly technologies for brick manufacturing, such as cleaner fuel sources or kiln designs. The study can inform policy formulation to promote sustainable brick manufacturing, such as emissions standards or incentives for adopting cleaner technologies. Stakeholder engagement is critical to the success of any sustainability initiative. Future studies should engage with brick manufacturers, policymakers, and other stakeholders to ensure the results of the study are relevant and useful for decision-making.

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Nomenclature

AQI	Air Quality Index
BC	Black Carbon
BKOAP	Brick Kiln Owners Association of Pakistan
FCBTK	Fixed Chimney Bull's Trench Kiln
GHG	Greenhouse Gases
HHK	Hybrid Hoffmann Kiln
ICIMOD	International Centre for Integrated Mountain Development
IDZK	Induced Draft Zigzag Kiln
LCA	Life Cycle Assessment
NEECA	National Energy Efficiency and Conservation Authority
PM	Particulate Matter
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
SEC	Specific Energy Consumption
TA	Terrestrial Acidification
TK	Tunnel Kiln
VSBK	Vertical Shaft Bull's Trench Kiln
ZZK	Zigzag Kiln

References

1. Lee, J. Cost evaluation methodology that can be used in a 3D architectural design environment. *Int. J. Adv. Res. Eng. Technol.* **2020**, *11*, 97–103.
2. Brick Development Association. Sustainability Report Chairman's Summary. 2019. Available online: https://www.brick.org.uk/uploads/downloads/Sustainability-Report-2019.pdf (accessed on 26 February 2023).
3. Pervaiz, S.; Ameer, M.; Akram, N.; Khan, F.Z.; Javid, K. Brick Sector and Air Quality: An Integrated Assessment towards 2020 Challenge of Environment Development. *Environ. Nat. Resour. J.* **2021**, *19*, 153–164. [CrossRef]
4. Ncube, A.; Matsika, R.; Mangori, L.; Ulgiati, S. Moving towards resource efficiency and circular economy in the brick manufacturing sector in Zimbabwe. *J. Clean. Prod.* **2021**, *281*, 125238. [CrossRef]
5. Kumbhar, S.; Kulkarni, N.; Rao, A.B.; Rao, B. Environmental life cycle assessment of traditional bricks in western Maharashtra, India. *Energy Procedia* **2014**, *54*, 260–269. [CrossRef]
6. World Population Prospects 2022. 2022. Available online: https://population.un.org/wpp/ (accessed on 26 February 2023).
7. Abdul, S.; Al-motairi, H.; Tahir, F.; Al-fagih, L. Incentives and strategies for financing the renewable energy transition: A review. *Energy Rep.* **2021**, *7*, 3590–3606. [CrossRef]
8. Ali, M.; Wazir, R.; Imran, K.; Ullah, K.; Janjua, A.K.; Ulasyar, A.; Khattak, A.; Guerrero, J.M. Techno-economic assessment and sustainability impact of hybrid energy systems in Gilgit-Baltistan, Pakistan. *Energy Rep.* **2021**, *7*, 2546–2562. [CrossRef]
9. Adopt, T.; Environmental, A. To Adopt, or Not to Adopt, Why is the Question: An Environmental and Economic Case for Zigzag. Available online: https://cdpr.org.pk/wp-content/uploads/2019/04/010819-SN-IGC-Brick-Kiln-Project.pdf (accessed on 26 February 2023).
10. Elsoragaby, S.; Yahya, A.; Razif, M.; Mat, N. Applying multi-objective genetic algorithm (MOGA) to optimize the energy inputs and greenhouse gas emissions (GHG) in wetland rice production. *Energy Rep.* **2020**, *6*, 2988–2998. [CrossRef]
11. Government of Pakistan. 2020. Available online: https://www.solidaritycenter.org/wp-content/uploads/2021/03/Pakistan.Report.Forced-labor-in-the-brick-kilns.pdf (accessed on 26 February 2023).
12. Lin, B.; Raza, M.Y. Coal and economic development in Pakistan: A necessity of energy source. *Energy* **2020**, *207*, 118244. [CrossRef]
13. Jain, P.; Bansal, S. Brick Kilns, Anemia & Residential Proximity: Evidence from Bihar. Available online: https://www.isid.ac.in/~epu/acegd2022/papers/Parul_Jain.pdf (accessed on 26 February 2023).
14. Maraveas, C. Production of sustainable construction materials using agro-wastes. *Materials* **2020**, *13*, 262. [CrossRef]
15. Lakshmi, N. Issue 2 Page 780 International Journal of Community Medicine and Public Process evaluation of mission Indradhanush immunization program in urban and rural communities of Ahmedabad district of Gujarat. *Int. J. Community Med. Public Health* **2022**, *2*, 2–6.
16. Anwar, M.N.; Shabbir, M.; Tahir, E.; Iftikhar, M.; Saif, H.; Tahir, A.; Murtaza, M.A.; Khokhar, M.F.; Rehan, M.; Aghbashlo, M.; et al. Emerging challenges of air pollution and particulate matter in China, India, and Pakistan and mitigating solutions. *J. Hazard. Mater.* **2021**, *416*, 125851. [CrossRef] [PubMed]
17. Zavala, M.; Molina, L.T.; Maiz, P.; Monsivais, I.; Chow, J.C.; Watson, J.G.; Munguia, J.L.; Cardenas, B.; Fortner, E.C.; Herndon, S.C.; et al. Black carbon, organic carbon, and co-pollutant emissions and energy efficiency from artisanal brick production in Mexico. *Atmos. Chem. Phys.* **2018**, *18*, 6023–6037. [CrossRef]
18. Galliero, G.; Volz, S.; Galliero, G.; Volz, S. Thermodiffusion in model nanofluids by molecular dynamics simulations. *J. Chem. Phys.* **2008**, *128*, 064505. [CrossRef] [PubMed]

19. Allen, M.R.; Stocker, T.F. Dioxide emissions. *Nat. Clim. Chang.* **2014**, *4*, 23–26. [CrossRef]
20. Urbana-champaign, I. Brick Kiln Measurement Guidelines: Emissions and Energy Performance. 2016. Available online: https://www.ccacoalition.org/sites/default/files/resources/BC_BrickKilns_GuidanceDocument_Final.pdf (accessed on 26 February 2023).
21. Nations, U.; Programme, E. Brick Kiln Emission-Energy Study in Pakistan. 2019. Available online: https://www.mdpi.com/2071-1050/12/18/7724 (accessed on 26 February 2023).
22. No New Brick Kiln to Be Allowed Sans Zig-Zag Firing Tech: EPD. DAWN. Available online: https://www.dawn.com/news/1408569 (accessed on 26 February 2023).
23. ICIMOD. Building Back Better Brick Kilns in Nepal. 2016, pp. 2015–2016. Available online: http://lib.icimod.org/record/32300 (accessed on 26 February 2023).
24. Mehrparvar, A.H.; Hossein Davari, M.; Mollasadeghi, A.; Reza Vahidi, M.; Mostaghaci, M.; Bahaloo, M.; Shokouh, P. Case Report Hearing Loss due to Carbon Monoxide Poisoning. *Case Rep. Otolaryngol.* **2013**, *2013*, 14–17.
25. Sulfur Dioxide Effects. EPA. Available online: https://archive.epa.gov/clearskies/web/pdf/overview.pdf (accessed on 26 February 2023).
26. Zhang, H.; Magara-Gomez, K.T.; Olson, M.R.; Okuda, T.; Walz, K.A.; Schauer, J.J.; Kleeman, M.J. Science of the Total Environment Atmospheric impacts of black carbon emission reductions through the strategic use of biodiesel in California. *Sci. Total Environ.* **2015**, *538*, 412–422. [CrossRef]
27. Solomon, S. Risks to the stratospheric ozone shield in the Anthropocene This article belongs to Ambio's 50th Anniversary Collection. Theme: Ozone Layer. *Ambio* **2021**, *50*, 44–48. [CrossRef] [PubMed]
28. Methane: A Crucial Opportunity in the Climate Fight. Available online: https://www.edf.org/climate/methane-crucial-opportunity-climate-fight (accessed on 26 February 2023).
29. Publications of the Institute of Geophysics Polish Academy of Sciences. 2020, Volume 429. Available online: https://pub.igf.edu.pl (accessed on 26 February 2023).
30. *ISO 14040 2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: London, UK, 2006.
31. Santos, S.D.F.d.O.M.; Piekarski, C.M.; Ugaya, C.M.L.; Donato, D.B.; Júnior, A.B.; De Francisco, A.C.; Carvalho, A.M.M.L. Life Cycle Analysis of Charcoal Production in Masonry Kilns with and without Carbonization Process Generated Gas Combustion. *Sustainability* **2017**, *9*, 1558. [CrossRef]
32. Mendes, L.; De Francisco, A.C.; Piekarski, C.M.; Salvador, R. Integrating life cycle assessment in the product development process: A methodological approach. *J. Clean. Prod.* **2018**, *193*, 28–42. [CrossRef]
33. Salvador, R.; Piekarski, C.M.; Mendes, L.; De Francisco, A.C. Life Cycle Assessment of Electricity from Biogas: A Systematic Literature Review. *Environ. Prog. Sustain. Energy* **2019**, *38*, 13133. [CrossRef]
34. Koroneos, C.; Dompros, A. Environmental assessment of brick production in Greece. *Build. Environ.* **2007**, *42*, 2114–2123. [CrossRef]
35. Huarachi, D.A.R.; Gonçalves, G.; de Francisco, A.C.; Canteri, M.H.G.; Piekarski, C.M. Life cycle assessment of traditional and alternative bricks: A review. *Environ. Impact Assess. Rev.* **2020**, *80*, 106335. [CrossRef]
36. Galan-marin, C.; Rivera-gomez, C.; Garcia-martinez, A. Use of Natural-Fiber Bio-Composites in Construction versus Traditional Solutions: Operational and Embodied Energy Assessment. *Materials* **2016**, *9*, 465. [CrossRef] [PubMed]
37. Huang, B.; Chen, Y.; Mcdowall, W.; Türkeli, S.; Bleischwitz, R. Embodied GHG emissions of building materials in Shanghai. *J. Clean. Prod.* **2019**, *210*, 777–785. [CrossRef]

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