sustainability

MDPI

Review

Traditional Brick Making, Environmental and Socio-Economic Impacts: A Case Study of Vhembe District, South Africa

Tolulope E. Aniyikaiye [1,*], Joshua N. Edokpayi [2], John O. Odiyo [3] and Stuart J. Piketh [4]

1 Department of Geography and Environmental Science, University of Venda, Private Bag X5050, Thohoyandou 0950, South Africa
2 Department of Earth Sciences, University of Venda, Private Bag X5050, Thohoyandou 0950, South Africa; Joshua.Edokpayi@univen.ac.za
3 Office of The DVC Research Innovation Commercialisation and Internationalisation (RICI), Vaal University of Technology, Vanderbijlpark 1901, South Africa; john.odiyo@univen.ac.za
4 Unit for Environmental Sciences and Management, North West University, Potchefstroom 2520, South Africa; Stuart.Piketh@nwu.ac.za
* Correspondence: lizaniyi@gmail.com; Tel.: +27-73-949-5957

Abstract: The brick making industry, despite its contribution to environmental pollution, plays a major role in the economic growth of South Africa, with the traditional technology accounting for a significant proportion of the total clay brick production. The aim of this study is to undertake a comprehensive description of the production phases of the traditional brick making sector in Vhembe district and how this contributes to air pollution. The study comprised a series of interviews and questionnaires of key role players from two small villages, Manini and Tshilungoma in the Vhembe district. In-situ observations of the production methods and phases were also undertaken between June and December 2019. The brick making production phases used in Vhembe district are excavation, preparation, moulding, drying and firing. An average estimate of 34,683 bricks is fired monthly per brick kiln in Vhembe district. Emissions from brick making organisations had resulted into several public health and environmental risks. To reduce environmental degradation, the incorporation of industrial and environmental wastes into brick making and the gradual transition to environmentally friendly technology such as Vertical Shaft brick kiln (VSBK) should be embraced. Thus, traditional brick making implemented with appropriate sustainable environmental technology has the potential to improve the socio-economic status of the brick makers.

Keywords: atmospheric emissions; environmental impacts; production phases; socio-economic impacts; traditional brick making; Vhembe district; VSBK

Citation: Aniyikaiye, T.E.; Edokpayi, J.N.; Odiyo, J.O.; Piketh, S.J. Traditional Brick Making, Environmental and Socio-Economic Impacts: A Case Study of Vhembe District, South Africa. *Sustainability* **2021**, *13*, 10659. https://doi.org/10.3390/su131910659

Academic Editor: Constantinos Cartalis

Received: 17 August 2021
Accepted: 4 September 2021
Published: 25 September 2021

1. Introduction

Currently, clay brick is one of the most popular and preferred construction material in many parts of the world [1–5] due to their high tensile strength, resilience, thermal and sound insulation, fire and weather resistance [6]. The scarcity of wood and construction stones was reported to have brought about the use of clay brick as substituting construction material [4]. Clay bricks basically supply construction component with definite set of thermal and structural properties that could be supplemented with other kinds of construction medium for building a barrier between the interior and external environments [7].

Brick making is recognised as one of the key contributors to economic growth in many parts of the world such as South Africa, Bangladesh, India and Ghana [2,8–10]. Across the globe, bulk of brick production is attributed to unorganised small-scale industry that employs the use of energy inefficient traditional techniques [3,8–12]. Large-scale brick firing in South Africa, as well as other parts of Africa, Asia and Central America is predominantly by clamp kiln technology. This could be attributable to its relatively simple and economic technological application, in comparison with other firing techniques [13,14]. South Africa is known to be the largest producer of clay brick contributing over 70% of the total production volume for the Southern African Development Countries (SADC) [15]. In South Africa, about 100 brick making industries manufacture approximately 3.5 billon bricks annually with 73% from Clamp kilns [15]. Contributions from other firing technologies include: tunnel (14%), Hoffman (4%), Vertical Shaft brick kiln (VSBK) (2%), Transverse arch kiln (6%), Bull Trench kiln (BTK) (1%).

The informal brick making industry (IBMI) is an unlicensed small-scale business, thus sparse information is known about this business, in terms of the operational mode, production procedures, environmental and socio-economic impacts on the host community. Brick making is a labour-intensive business, carried out seasonally mostly during the dry seasons [1,8]. The informal brick making industries (IBMIs) are usually in clusters located in peri-urban and suburb regions [12], along waterfronts [11,15] close to clay sources [16]. Based on production capacity, Swiss Contact and CBA [15] defined traditional brick making sector as the brick making industry with relatively small monthly production figure of about 60,000 bricks per person. The industry employs the use of various materials and production techniques with unpredictable success [15]. Examples of the traditional technology includes clamp kilns, fixed bull trench kilns, scove and scotch [3,9,12,15,17].

Furthermore, traditional brick making in communities across Africa, Asia and Latin America, is organised as family-owned micro and cottage businesses serving the needs of their immediate environments [1]. Based on the socio-economic importance of informal brick manufacturing sector, proximity of manufacturing facilities to raw material as well as the use of inexpensive instruments and fuel, reduces the cost of production, hence maximising profit [16,18]. The brick making business is often established to generate minimum income for the jobless and unskilled laborers, for the upkeep of their families. However, income generated from these activities is below the minimum income standard [18,19]. The study conducted by Swiss Contact and CBA [15] in South Africa, indicated the existence of over 1000 informal brick making industries with more than 5000 employees.

Generally, the traditional brick kiln is associated with the release of atmospheric emissions without restriction due to its energy inefficient crude innovation [20], and the absence of mitigation measures [3]. Akinshipe [14] stated that the predominant source of fuel for South African clamp kiln is coal made from either peas or small nuts, carbon fly ash (CFA) and duff coal. However, the use of wood and farm waste such as macadamia nuts is most prevalent in the informal brick making industry in South Africa [15] as shown in Table 1. Burning of coal and diverse biomass fuels during brick firing results in the generation of particulate and gaseous emissions with adverse effects on the human health and the surrounding plants [8].

Table 1. Attributes of bricks manufactured through traditional techniques in the developing countries.

Country	Types of Traditional Firing Kiln Used	Market Share from the Informal Sector	Fuel Used for Firing in Informal Sector	Fired Brick Dimension (mm)	Average Weight of Fired Brick	Author
Botswana	Clamp	5%	fly ash, coal duff, small coal nuts	220 × 110 × 75	3.0 Kg	Swiss contact and CBA [15]
Madagascar	Scove, Bull Trench Kilns	25%	Rice husks, agricultural wastes, peat, coal, ash, wood	NR	NR	
Malawi	Clamp and scove	50%	Ricehusks, wood Charcoal, and wood, dry leaves	230 × 110 × 70	2.8	
Mozambique	Clamp	50%	coal, ash, charcoal, wood and farm waste.	NR	NR	
Namibia	Clamp	NR	Charcoal and coal	220 × 100 × 50, 220 × 110 × 75	1.6 Kg 3.0 Kg	
South Africa	Clamp and scove	50%	fly ash or coal, wood and farm waste (macadamia husks)	220 × 150 × 75	NR	
Tanzania	Clamp	100%	rice husks, cotton wastes	220 × 150 × 75		
Zambia	Clamp	10%	charcoal and wood	220 × 110 × 75	3.0 Kg	
Zimbabwe	Clamp	12.5%	Coal, charcoal, and wood and fly ash	220 × 110 × 75	3.4 Kg	

Table 1. *Cont.*

Country	Types of Traditional Firing Kiln Used	Market Share from the Informal Sector	Fuel Used for Firing in Informal Sector	Fired Brick Dimension (mm)	Average Weight of Fired Brick	Author
India	[a] Clamp, Movable Chimney BTK, fixed Chimney BTK	NR	[b] Biomass, coal and lignite	NR	[a] 3.0 Kg	Maithel et al. [1]; Uma et al. [3]
Uganda and Tanzania	NR	NR	Wood from locally grown trees, coffee/rice husks	220 × 110 × 65	2 Kg	Hashemi et al. [5]
Sudan	NR	<98%	Fuelwood, charcoal, agricultural residue (cotton stocks, groundnut shells, bagasse, animal dungs)	190 × 100 × 50	NR	Alam et al. [11]
Vhembe District, South Africa	clamp	73%	Fuelwood, macadamia nut shell	(200–224) × (112–127) × (70–85)	3.5 Kg	This study

a—Maithel et al. [1]; b—Uma et al. [3]; NR—Not reported.

Several studies have been conducted on the statistical analysis on the various types of firing technologies as well as emissions from brick making industries in the developed countries [3,8,13]. To the best of our knowledge, no study has explicitly described traditional brick making techniques, the environmental and socio-economic implications in rural settings like the Vhembe district, Limpopo province of South Africa. The primary hypothesis this study seeks to test is: What are the current processes of traditional brick making industries in a rural setting and are the firing techniques efficient? Secondarily, the study is sought to establish the socioeconomic status of brick makers as well as the impact of brick making on the health of the brick workers and their immediate environment.

Historical Perception of Brick Making

The art of masonry and 'stone dressing' from time immemorial to about 2500 BC originated in Ancient Egypt [21]. Clay bricks began from Mehrgarh in 7000 BC during pre-Harappa time [1,22]. Mason and Lee [23] stated that the deposition of mud which cracks and forms cake on the Nile, Euphrates, or Tigris rivers after flooding initiated moulding into crude building units for construction of sheds. Availability, flexibility as well as economical production of clay bricks in comparison with stones resulted in the gradual shift in construction material from stone to clay brick [24].

The first true building of sun-baked brick was made about 4000 BC in Mesopotamia now known as Iraq [23]. Primitive brick units basically made up of mixture of mudbricks with straw were extensively used before the advent of technological advancements resulting in the production of fired bricks [25]. Baked brick technology emerged in the Indus Valley culture [1,22]. Recently, fired clay bricks which are more durable, heat resistant and tough are produced via combustion of mud bricks in kiln [23]. The Mesopotamians were reported to have developed tougher and more durable bricks. The toughness and durability features in bricks produced in Mesopotamia was attributed to the baking of bricks produced from the combination of clay and straw [21]. Amanda [21] emphasised that the toughness as well as lightness of the bricks makes it relatively easier for stacking, loading and transporting without damage, an added advantage of fired brick over the use of stone.

Fired clay bricks was introduced in South Africa during the first year of Jan van Riebeeck's arrival in Cape. In August 1654, the first house made with red fired bricks was constructed in Cape. Mass production of bricks was initiated in Africa in the year, 1655 [15]. However, Clay brick production became popular in South Africa during the period of British occupation in 1795 [15]. The most common brick dimension for construction purpose is 5.5 × 9.5 × 20 centimetres [23]. In the 19th Century, various innovations serving as the bedrock for the current industrial brick making technology were invented in Europe and the USA. The innovations include extruder and press for shaping of bricks, Hoffmann and tunnel kilns for burning of bricks and chamber drier [1]. Industrial revolution conceived the transition from manual method to automated mass production of bricks resulting in the explosion of brick as a modern building material, hence the preferred material for commercial buildings [7,25].

2. Materials and Methods

2.1. Study Area

Vhembe District Municipality has geographic coordinates 22.7696° S, 29.9741° E and is located in the northern region of Limpopo province. It shares boundary with Zimbabwe and Botswana in the north-west and Mozambique in the south-east through the Kruger National Park [26].

The Limpopo River serves as demarcation between the district and its international surroundings. It covers a geographical area that is mostly rural. The district is subdivided into four municipalities namely: Musina, Thulamela, Makhado and Collins Chabane. It is endowed with a wide expanse of land covering 25,596 km^2 and has a population of about 1.5 million [26]. Mining and agriculture are the major means of livelihood [26].

Vhembe District has a high number of brick-making industries that can be divided into the formal and informal sectors. However, Vhembe District is predominated by the IBMIs. The impacts of the IBMIs have been evaluated in two regions of Limpopo in this study, namely Manini and Tshilungoma (Figure 1). The presence of clay deposits as well as water bodies in these regions of the province make them attractive locations for brick makers. The small-scale informal producers were selected because sparse information is known about this business, in terms of the production procedures, environmental and socio-economic impacts in Vhembe community. Furthermore, evaluation of the brick making activities from the formal brick making industry (FBMI) in Lwamondo village, located in Vheme District, was carried out, as a basis of comparison with the traditional method of brick production.

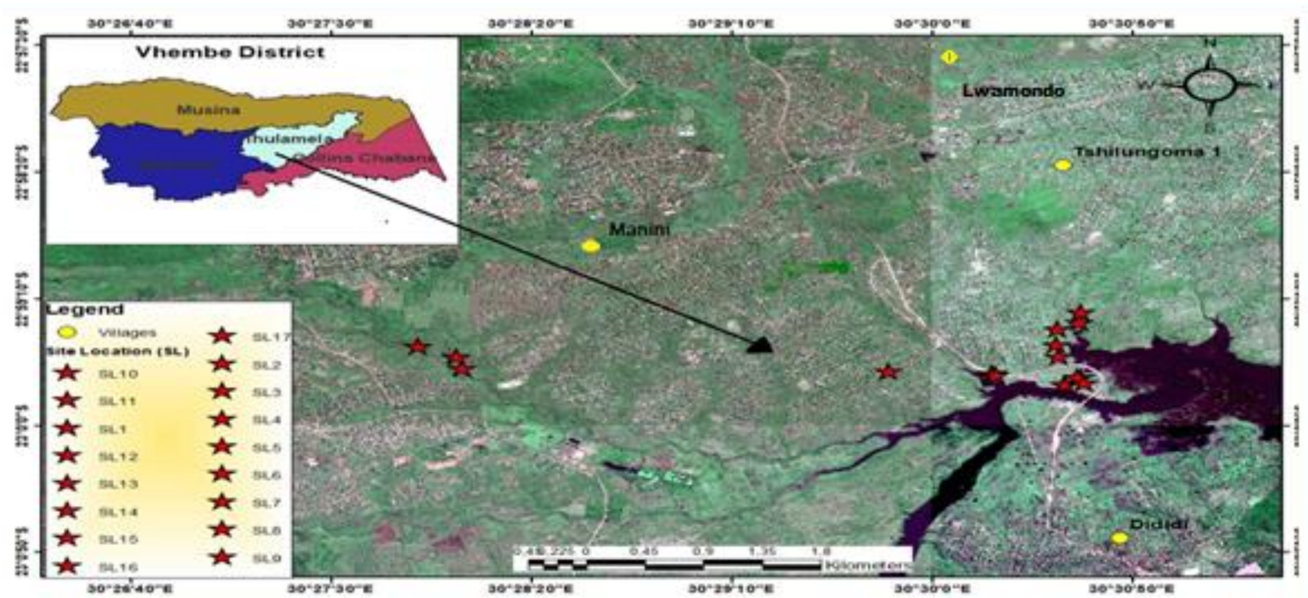


Figure 1. Map showing the selected sites in Vhembe District.

2.2. Methodology

This study explores the use of literature to establish the socioeconomic, health and environmental impact of brick making on the brick workers and the environment. In addition, quantitative data were obtained during a field survey to establish the phases of traditional brick making in Vhembe District of South Africa. For the review, Google Scholar, Research Gate, Science Direct, PubMed, Taylor and Francis and Ebscohost databases were used to search for keywords related to brick making (Figure 2a). Keywords such as traditional brick making, environmental and health impacts of traditional brick making, production phases of traditional brick making, socioeconomic impacts of traditional brick making, atmospheric emissions from brick making and efficiency of Vertical Shaft brick kiln (VSBK) were used during the publication search. The categories of publications used for the review and their proportions are displayed in Figure 2b. Publications made between 1980 and 2021 were harvested and used for the review (Figure 2c).

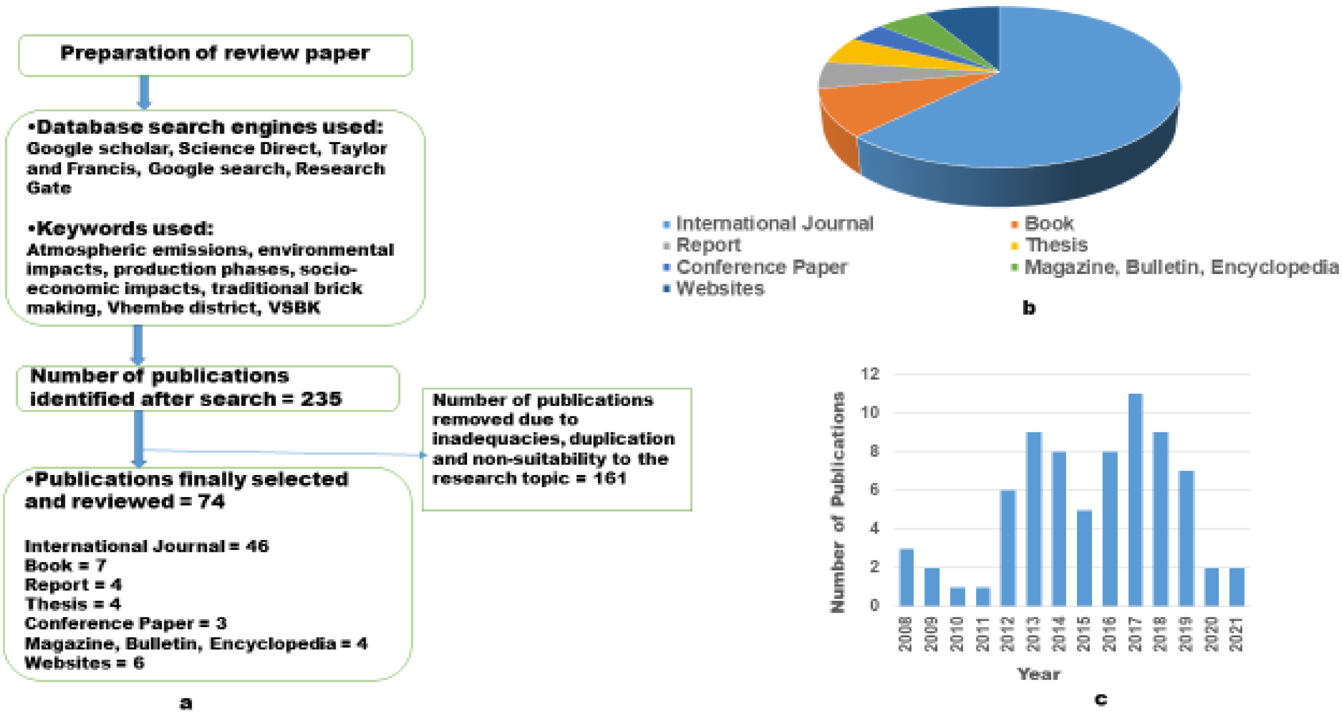


Figure 2. Method used for the review. (**a**) Flow chart for the for the review process; (**b**) The categories of publications used for the review and their proportions; (**c**) Yearly distribution of publications for extracting data.

The study was conducted between June and December 2019. Ethical clearance (SES/19/ERM/08/1309) was obtained from the University of Venda Research and Ethics Committee before conducting the survey. Information was obtained mainly through observations from field survey as well as interviews using questionnaires. A questionnaire drafted in English and Tshivenda dialects, was used as a medium for collection of relevant data from the local brick makers. For clarity purpose, the questionnaire was administered to them on their language of choice. Questionnaires in Tshivenda dialects were administered to the brick makers through the assistance of an interpreter. The template was made up of questions which covered aspects such as demography, process, environmental and socio-economic issues experienced by the local brick makers. The informal brick makers were assured of the confidentiality of their data before the commencement of the questionnaire administration. Participation of the respondents in the survey was based on willingness.

A pilot test was first conducted using participants having similar characteristics with the intended group, after which necessary adjustments were made on the questionnaire prior to conducting the survey. The survey was carried out during the working hours of the brick makers. The survey covered a large range of respondents with varying characteristics. The questionnaire was administered in the form of interview to 38 informal brick makers from 17 functioning brick kilns based on their willingness to participate. The questionnaires were administered to the brick makers in their brick yards while they were working or during their resting periods. The questions were drafted based on previous interviews with the brick makers and items from questionnaires of similar studies. Each questionnaire took between 15 to 20 min to complete. Several of the brick makers in the two villages surveyed, were visited in their brick yard during work hours in both winter and summer season to verify the processes as well as the technical data collected from the questionnaire.

Additionally, field activity data which includes parameters such as types and quantities of fuel used for brick firing, amount of bricks fired and duration of burning were collected from IBMIs and the selected FBMI in Vhembe district between June 2019 and December 2019. The corresponding energy contents of the various fuels used by clamp kiln (traditional technology) and that of VSBK (the modern and cleaner technology used in the selected FBMI) were determined. Comparison between the energy use for the combustion of 1000 bricks with the clamp kiln and VSBK was carried out, and energy reduction obtainable with transition from the clamp kiln to VSBK was also determined.

Data collected through questionnaire were computed and statistically evaluated using Excel 2013 and IBM SPSS version 25 statistical packages. The descriptive statistical tool of the IBM SPSS was used to analyse the survey data.

3. Results

3.1. Operational Mode of the Informal Brick Making Industry

The informal brick making industries (IBMI) in the study area were in clusters along waterfronts due to the availability of huge deposits of clay. Modiselle [27], indicated that massive deposits of clay are often formed from secondary sedimentary deposition process as a result of erosion from their source of formation. The clayey soil is usually found closer to the top soil making it less expensive to access [27]. Cermalab [19] in his survey in Eastern Cape, South Africa also noted the location of informal brick making sectors along watercourses or dams where water is easily accessible. Findings from this study showed that majority (44.7%) of the respondents obtain water for brick production from nearby river. However, the sources of water used by remaining participants and their respective proportions include: dam; (31.6%), well; (21.1%) and tap; (2.6%). Unlike in Manini where the only source of water for the local brick production factories is a river, Tshilungoma village has various sources of water for brick manufacturing such as wells, dam, river and taps.

The daily working hours of the local brick makers in the study area span from 6H00 to 18H00, although the number of hours vary from one brick site to the other. Over 70% of the brick yards operate between 10 and 12 h daily while the respective proportions for other work durations in the survey are as follows: 1–3 h; (2.6%), 4–6 h; (5.3%) and 7–9 h; (18.4%). The result in this study is in congruent with the study carried out by Das et al. [28] in Bangladesh, in which 60.7% of the respondents claimed to work more than 8 h daily (see Table 2). Kazi and Bote [29] described brick making as an unskilled, low paying job involving the use of strenuous physical labour for several hours.

Table 2. Socio-economic status of brick kiln workers.

This Study (n = 38)		**Kazi and Bote, [29] (n = 420)**		**Das et al., [28] (n = 402)**		**Sanjel et al., [30] (n = 400)**	
Age	**%**	**Age (Years)**	**%**	**Age (Years)**	**%**	**Age (Years)**	**%**
<18 years	5.3					≤19	20.2
18–27 years	39.5	18–25	21.9	20–25	5.72	20–29	29.8
28–37 years	36.8	26–40	51.7	26–30	31.59	30–39	21.0
38–47 years	13.2	>40	26.4	31–35	41.79	40–49	17.0
47–57 years	0			36–40	19.15	50–59	8.2
>57 years	5.3			>40	1.74	60–69	2.8
						≥70	1.0
Total	100.0		100.0		100.0		100.0

Table 2. *Cont.*

This Study (n = 38)		Kazi and Bote, [29] (n = 420)		Das et al., [28] (n = 402)		Sanjel et al., [30] (n = 400)	
Age	**%**	**Age (Years)**	**%**	**Age (Years)**	**%**	**Age (Years)**	**%**
Years of Experience							
<4 year	63.1					≤5 years	66.2
4–6 years	13.2			≤6 years	60.45	6–10 years	15.8
7–9 years	5.3	≤5	37.1	>6 years	39.55	11–15 years	7.5
>9 years	18.4	6–10	35.7			16–20 years	5.8
		>10	27.2			≥21 years	4.8
Total	100.0		100.0		100.0		100.0
Daily Work duration							
1–3 h	2.6	NR				NR	
4–6 h	5.3			7–8 h	39.30		
7–9 h	18.4			8–9 h	33.08		
≥10 h	73.7			≥10 h	27.61		
Total	100.0				100.0		

NR: Not reported.

In addition, about 75% of the brick makers claim to produce all through the year except occasionally on rainy days. However, other brick kiln operators stated that they do not work during the wet season. Cermalab [18] ascribed the seasonality of brick making in some areas to the existence of unfavourable atmospheric conditions or low demand for bricks. However, the brick kiln operates throughout the year in some semi-urban localities [18]. This is in line with some of the reasons given by the interviewed brick makers for non-production throughout the year. The reasons given include: rain disturbances, water logging of mining areas, low demand and sales of fired bricks during summer and traveling to home country for vacation. Mazumdar et al. [31] claimed water lodging of quarried land as a major challenge on brick making industries [31]. Islam and Roy [32] further attributed water logging to accumulation of water in the low-lying excavated land. In addition, the absence of permanent roof for protection of the bricks from rain in the informal brick making sector makes the uninterrupted production of bricks in the year impossible.

3.2. The Traditional Brick Making Processes

For the Informal brick making sectors in Vhembe district, there are 5 major stages of brick production as shown in Figure 3.

Figure 3. Stages of Brick Production.

Excavation stage: Excavation is the first stage in brick production which involves the mining of ground for suitable soil for brick production. Manual tools such as shovel, wheelbarrow and bucket are generally employed [18]. Any available soil within the vicinity regardless of the quality is used [18]. During this process, the soil is dug with the digger, topsoil is removed, and the ground height reduced (Figure 4a). Soil particles or dust released during this process, are conveyed through wind erosion with consequential effects on human life. Shahram et al. [33] has reported the impact of dust on respiratory, cardio-vascular, cerebral-vascular systems of humans. Dust particles weaken the deoxyribonucleic acid (DNA) of skin and lung cells, they as well exacerbate meningitis, fever, pain, allergies, and viral infections [33].

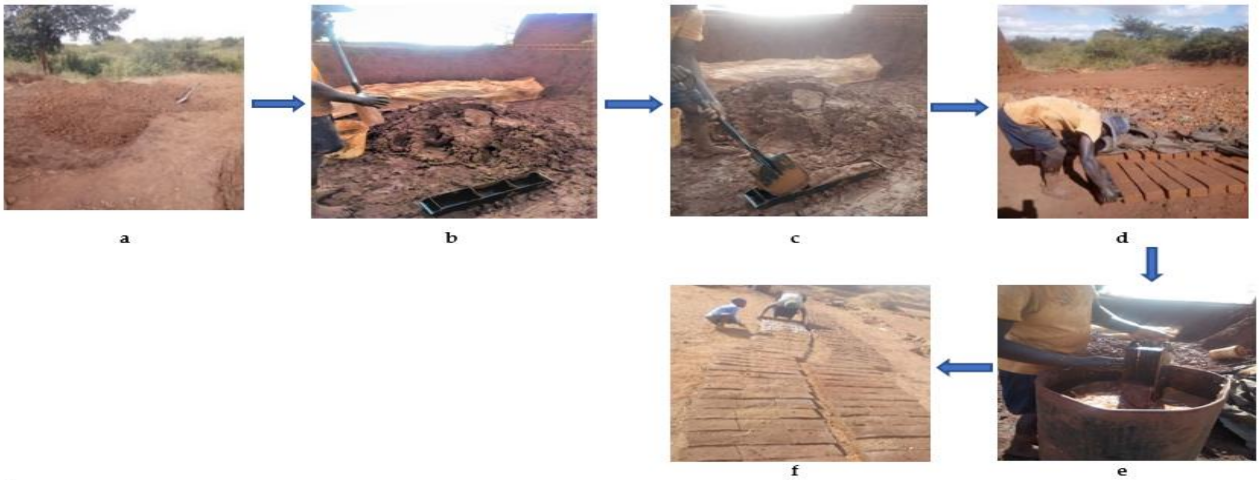


Figure 4. Excavation, Preparation and Moulding Processes. (**a**) Excavation of soil with digger and shovel; (**b**) Covering of the unused mortar portion to prevent evaporation; (**c**) Filling and levelling of mould content with shovel; (**d**) Inversion of mould to extrude the content; (**e**) Washing of mould prior to refilling with mortar; (**f**) Sequential arrangement of wet bricks for drying and pouring of sand on the wet bricks.

Excavation leaves the soil loose, hence prone to flooding during rainy season [29]. In addition, the loose soil could be carried by wind, resulting in deterioration of soil quality along the wind direction [2]. Mining in the informal brick making sector is a manual activity which involves the elimination of vegetation and the excavation of soil from top to bottom including the topsoil and the overburden [18]. Soil mining has negatively affected the local environment contributing to issues such as deforestation [11,20], desertification, air pollution, excessive soil extraction [5,34] and removal of fertile topsoil for brick production [8,12,35,36].

Preparation: This is a process in brick making which comes up after excavation of soil. Prior to moulding, a portion of the excavated soil is gathered together in heap. Water is conveyed from a nearby water source either manually or through pump to the heap of sand. The survey indicated that half (50%) of the local brick makers in the two villages access the water manually while the remaining 50% of the respondents use pump. Water is transferred to the heaps of sand, stirred and re-shovelled continuously to allow penetration of water into the soil. The wet soil is then covered with plastic for about 24 h to enhance the softening of the lumps and the escape of bubbles. This also retards the evaporation of water from the mixture (Figure 4b). After 24 h, kneading of the soil is carried out by the brick makers using their bare feet. The essence of this is to break the existing lumps in the dough until a fairly homogeneous mixture is formed. This is done continuously for about 30 min to an hour. The separated portion is then remixed severally using the shovel; in the process stones and hard lumps found in the mortar are removed. This method of soil preparation is similar to the methods applied by Dalkilic and Nabikoglu [6], Alam [11] and Cermalab [18] from traditional brick making in Turkey, Sudan and Eastern Cape, South Africa, respectively (Table 3).

Table 3. The description of the various phases of Traditional brick making across the globe.

Author	**Dalkilic and Nabikoglu [6]**	**Alam [11]**	**Cermlab [18]**	**This Study**
Country/Location	Turkey	Sudan	Eastern-Cape, South Africa	Vhembe District, South Africa
Soil Excavation	Mechanical	Manual	Manual and mechanical (occasionally)	Manual
Raw material Preparation				
Materials used	Clay, straw and water	Clay, animal dungs and water	Clay, ash, duff and water	Clay and water
Wet clay fermentation duration	2–3 days	12 h	12–15 h	About 24 h
Moulding				
Method of moulding	Manual	Manual	Manual and mechanical (manually operated mechanical hand press)	Manual
Type of Mould	Wooden moulds of different sizes and shapes, opened at the top.	Steel and wooden moulds with 2 compartments but opened at both top and bottom	Rectangular Wooden mould opened at both bottom and top	Metallic mould with 3 compartments but opened at the top.
Precaution taken before filling the mould with the moist clay mixture	The mould is often coated with sand before filling with clay mixture	NR	The mould is often wetted with water before filling with clay mixture	Mould is often washed in a drum of water
Moulddimension(s) (mm)	200 × 390 × 50; 290 × 350 × 70; 250 × 350 × 60; 120 × 230 × 70; 100 × 200 × 60	210 × 100 × 55	NR	260 × 50 × 30
Drying				
Drying Method	Sun drying	Sun-drying	Open air drying	Open air drying
Duration for Drying	2–3 days	1–3 days	2 days	3–4 days
Firing				
Sub-divisions	Hacking, heating, firing, cooling and de-hacking,	Loading, firing, cooling and unloading.	Clamp construction, insulation, firing, cooling, de-hacking	Hacking, laying of protective layer, firing, cooling and de-hacking,
Fuel types	Coal, wood piece, and kerosene as fuel for firing.	Fuelwood, charcoal and agricultural wastes.	small coal nuts	fire wood (major) and macademia nut shell.
Description of kiln	The bottom part of kiln is made up of 2 rows of canals; the upper and lower canals for ignition and ventilation, respectively.		The first layer at the base provides a strong foundation for the kiln and allows the supply of air during combustion while the second layer of canal is filled with coal for firing.	The kiln is built with 4 to 6 fire boxes of dimensions (44 cm × 60 cm) at the bottom.
Initiation of firing		Ignition is initiated at the bottom and left to burn gradually until it reaches the top.	The fire is initiated by placing hot coals on top of the small nut coal in the fire boxes. Once the kiln is burning briskly, the fire boxes are covered with bricks and sealed with mud.	Logs of wood are inserted into the fire boxes, then ignition initiated by placing small pieces of wood, dry gases etc., on the logs of wood at the entrance of the fire boxes. Prior to sealing 4 to 6 logs of wood are vertically erected at each entrance of the fire boxes.
Protective layer for thermal insulation	A layer of protective covering is constructed round the dried bricks about to be fired and then plastered with mud	The outer layer and top of the kiln are covered with layer(s) of previously fired bricks and then plastered with mud premixed with animal dungs for insulation	The sides and the top of the kiln are covered with layers of previously fired bricks and the side plastered with mud.	A protective layer of previously fired bricks is constructed round and at the top of the kiln. The layer is then plastered with mud.
Duration for brick firing	15–60 days	24 h	NR	2–4 days
Duration for cooling	NR	1 week	2–4 weeks	3 days
Dimensions of fired bricks (mm)	190 × 375 × 40; 280 × 335 × 60; 240 × 335 × 50; 110 × 215 × 60; 90 × 185 × 50	190 × 100 × 50	(71–76) × (102–108) × (213–230)	(70–85) × (112–127) × (200–224)

NR: Not reported.

Moulding: Moulding is the phase of production after the preparatory stage, which transforms the clay soil into wet bricks of the desired shape and size. According to Weyant et al. [17], moulding is described as the shaping of the raw clay into brick by hand or with the use of mechanical extruder [17]. The hand-thrown method of moulding involving manual use of brick mould is employed for traditional brick making in Vhembe District. Generally, the rectangular shaped metallic brick mould with average dimensions: 70 cm × 12 cm × 9 cm, usually divided into 3 parts is used in the two villages examined.

The formed mortar is poured in a moist mould (Figure 4c), the mould is then filled and levelled using the shovel. The filled mould is conveyed to a prepared dried level ground (Figure 4d). In a situation where moist land is used, plastic is laid on moist ground prior to laying of the wet bricks. The plastic prevents the capillary movement of water molecules from the ground to the wet bricks. The mould is inverted gently to let out its content (wet bricks) (Figure 4d). The emptied mould is always washed in water before refilling to remove hanging clay mixture and to prevent deformity of the subsequent set of wet bricks (Figure 4e). The moulding technique employed is similar to the ones used in Turkey [6] and Eastern Cape, South Africa [18], except for the use of wooden moulds of various sizes and shapes, which are coated with sand [6] or wetted with water [18] before refilling with mortar (Table 2).

Successive batches of the wet bricks are aligned in a specified order as shown in Figure 4f. After moulding, a handful amount of sand is poured on the wet brick surface to prevent cracking and direct heat from the sun. Sand is sometimes added to achieve the right properties such as reduced drying shrinkage, drying sensitivity and firing range [18]. Twala [16] emphasised the necessity of adding at least 50% of silt and sand to the clay soil.

The daily production capabilities of the brick makers in Vhembe district vary from one brick kiln to the other. Findings from the survey indicated that the largest proportion (42.1%) of the respondents made 500–699 bricks per day. Other categories of daily production capabilities of the participants with their respective percentages are: Less than 300 (2.6%), 300–499 (5.3%), 700–899 (10.5%), 900–1099 (31.6%) and '1100 and above' (7.9%). Based on monthly production capacity of the examined informal brick making sectors, the predominant brick kiln capacity 41,000–60,000 accounts for 31.6% of the respondents while monthly production capacity of less than 5000, 5000–10,000, 11,000–20,000, 21,000–40,000 and above 60,000 were claimed by 2.6%, 13.2%, 28.9%, 10.5% and 13.2% of the respondents, respectively.

Drying: Drying is a process in brick production that involves the transformation of wet bricks into dry bricks. The transformation is enhanced by the evaporation of mechanical water from the wet brick. Green bricks are dried mechanically or by open drying using meteorological factors like the sun and wind [15,17]. In countries like South Africa, bricks are dried in open air to save resources [15,18]. In all IBMIs in Vhembe district, the natural air-drying method is used for brick production. Drying of the wet bricks per time is influenced by the prevailing meteorological conditions. Generally, bricks get dried on time on windy and sunny days, whereas drying time is extended on cloudy days. Findings from the survey showed that drying of bricks take an average of 3 and 4 days in summer and winter, respectively.

On rainy days, moulded and dried bricks are covered with plastic and sometimes channels are constructed around the land area where the bricks are laid to allow the flow of rainwater away from the laid bricks. When the rain ceases, the plastic is removed, and the drying process continued. After about 2 days of exposure of the moulded bricks to meteorological conditions for drying, the drying bricks are then repositioned to allow further drying. The stretcher (Figure 5a) or the header (Figure 5b) of the drying bricks are laid on the ground to allow flow of air and fast drying of the base initially placed on the ground, as well as other parts of the bricks. When the bricks are dried, they are packed and arranged using the header bond pattern (Figure 5c) on a dry levelled ground awaiting arrangement for clamp kiln.

(**a**) (**b**) (**c**)

Figure 5. Drying of bricks. (**a**) Laying of partially dried bricks on the stretcher for drying; (**b**) Laying of partially dried bricks on the header for further drying; (**c**) Packing of dried bricks.

Firing: Firing involves the burning of dried bricks. Firing of bricks is done to toughen and increase the durability of bricks. Majority of the brick makers (81.6%) in the two villages surveyed, use firewood while 18.4% supplement the use of firewood with macadamia nuts wastes. In total, 9.7% of the respondents stated that the quantity of fuel used for firing varies with season. The main reason for variation (increase in fuel usage) is the rain and partially dried brick during summer. The combustion of large quantities of firewood results in the generation of greenhouse gases (GHGs) such as water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) [11]. The significant release of GHGs is accountable for the outrageous environmental occurrences such as hurricanes, flooding and drought, which become progressively intense with further release of GHGs, prompting injuries, severe communicable maladies and deaths [37–39]. Health issues such as asthma and heart disease are linked to the atmospheric release of pollutants from the brick making industries [34]. Other symptoms such as severe cough, phlegm, bronchitis and wheezing are associated with brick making [30].

In addition, 50% of the respondents claim they fire the bricks monthly, while 13.2%, 26.3% and 7.9% of the respondents fire the bricks fortnightly, bimonthly and quarterly, respectively. On the average, 8 tonnes of wood are used to fire 19,000 bricks. From our study, an average estimate of 34,683 bricks is fired monthly per brick kiln in Vhembe district. In total, 6.7% of the respondents claim to fire less than 10,000 bricks monthly, whereas 10,000–30,000 bricks and 31,000 to 60,000 bricks are fired monthly by 46.7% and 46.6% of the participants, respectively.

In Vhembe district, the brick-firing phase of traditional brick production is sub-divided into 5 processes namely:

i. Hacking
ii. Laying of protective layer,
iii. Firing
iv. Cooling
v. De-hacking.

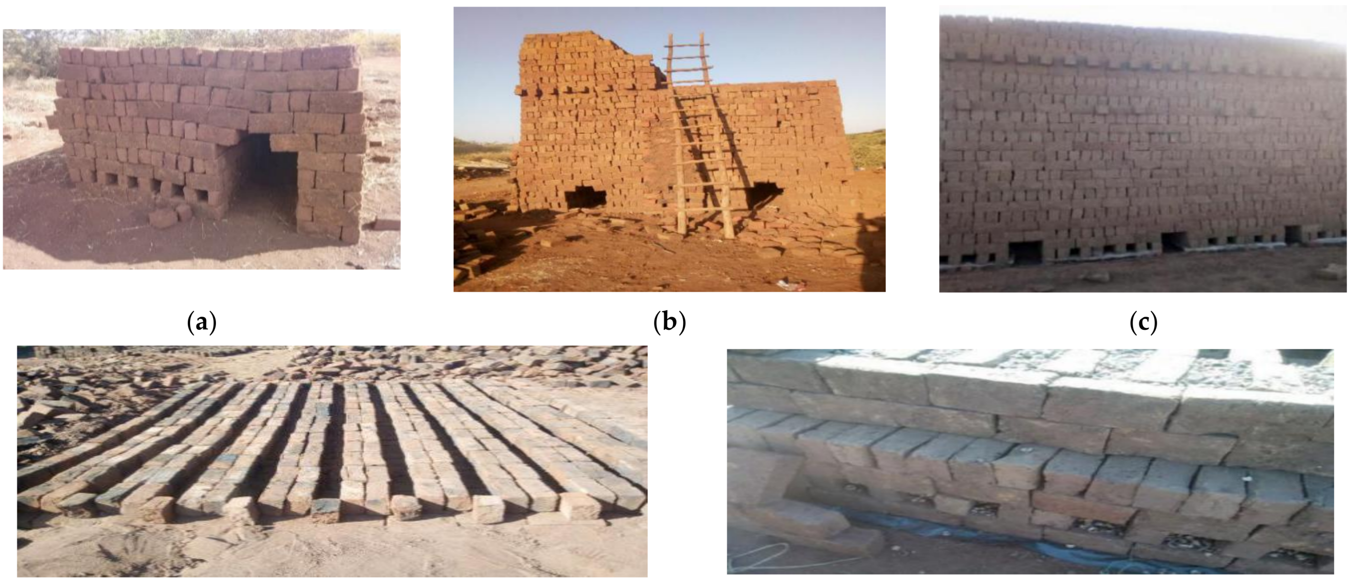
Prior to firing, the dried bricks are arranged into a temporal pyramidal structure on a dry levelled ground. The temporal pyramidal structure called clamp kiln is referred to as "Hondo" in Tshivenda. Brick firing for most brick makers is done at most once in a month. The number of bricks fired per batch varies from 10,000 to 60,000. In Vhembe district, fuel wood from gum tree (*Eucalyptus grandis*) (Figure 6a) is the most predominantly used fuel by the IBMIs. However, macadamia shells are sometimes used. Macadamia nut is a seasonal plant and the use of its shell (Figure 6b) for brick firing is relatively economical and environmentally friendly compared to firewood. Bada et al. [40] reported that macadamia shells contain relatively reduced ash content (0.36 wt%, db) and higher calorific value (19.64 MJ/Kg) compared to firewood which contains calorific value and ash content of 17.795 MJ/Kg and 1.17 wt%, db, respectively [41]. The use of macadamia shell could therefore serve as a good substitute to firewood.

(**a**) (**b**)

Figure 6. Types of fuel used for firing. (**a**) Firewood (gum tree) used in Vhembe district; (**b**) Macademia nut shell.

Hacking: Hacking involves the loading of dried bricks into the clamp kiln. Before loading of the dried bricks, the portion of land to be used for firing is prepared depending on the type of fuel to be used. When firewood is to be used as fuel for firing, the dried bricks are arranged on dry level ground. However, the floor preparation for firing when macadamia nut is to be used is more technical. The levelled ground meant for the oven is laid with macadamia nut before the loading of bricks. The dimension and size of the clamp kiln depend on available dried bricks.

The dried bricks are arranged into clamp kiln using the English bond pattern (Figure 7a). The bricks are usually piled up omitting rectangular portion of approximately 60 cm by 45 cm in 2 to 4 locations depending on the dimensions of the kiln. The rectangular openings called 'fire boxes' are channelled through the clamp kiln to the opposite side of the kiln. In Vhembe district, the clamp kiln is usually constructed with 2 to 4 big fire boxes at opposite sides, and small fire boxes at the adjacent sides. The number and dimension of the small fire boxes vary from kiln to kiln while that of the dimensions of the big fire boxes are alike. The big fire boxes serve as entrance for both large and thin logs of wood. Conversely, thin logs of wood especially fragmented firewoods are placed in the small fire boxes.



(**a**) (**b**) (**c**)

(**d**) (**e**)

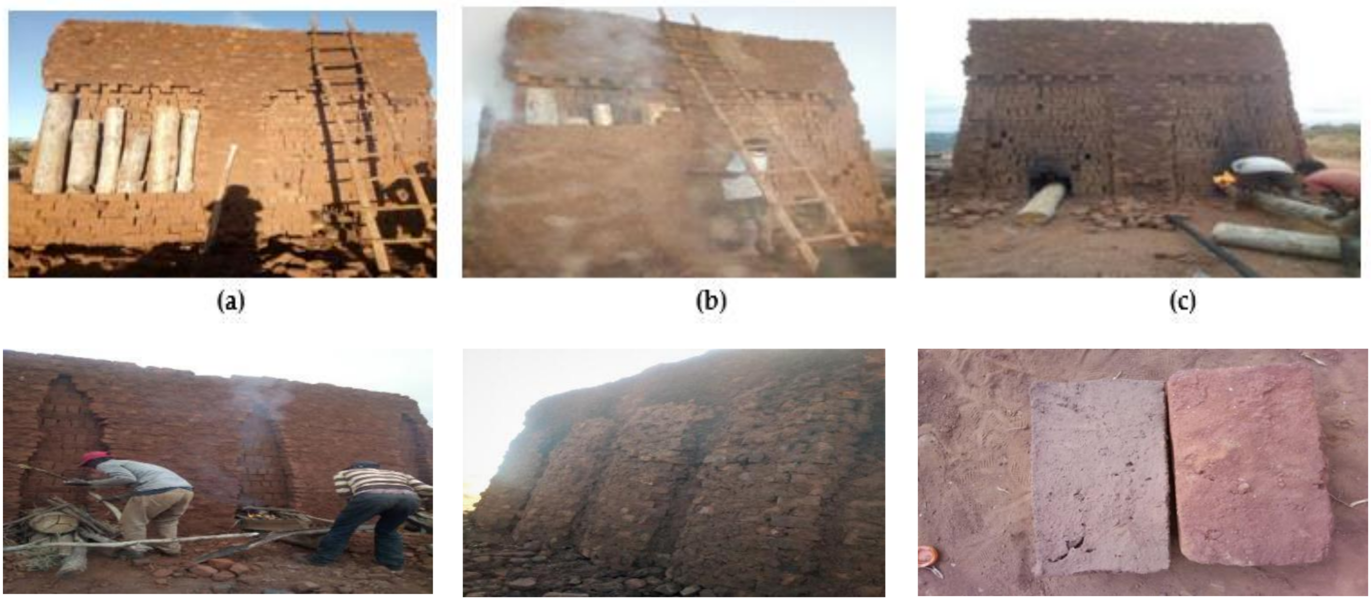
Figure 7. Hacking process of brick making. (**a**) Commencement of clamp kiln construction showing the big fire box; (**b**) 3 to 4 layers of bricks above the fire box in stretcher bond pattern; (**c**) Contours aligned at 2/3rd of the kiln height; (**d**) Foundation laying for brick-firing when macadamia nut is to be used as fuel; (**e**) Filling of the gaps in the 6th brick layer with macadamia nuts.

On constructing the big fire boxes, stretcher bond is used for the laying of the boundary layer to the next 3 to 4 layers after which the English bond pattern of arrangement is continued until the desired kiln height is achieved (Figure 7b). At about 2/3rd of the kiln height, a layer of header is used for formation of contours round the kiln (Figure 7c), besides the irregularly placed contours at about ¼ height of the kiln. The essence of these contours is to give support to the outer protective layer during arrangement.

For preparation of floor as well as arrangement of bricks with the use of macadamia nuts, the first lower layer of bricks is arranged axially lying on the stretcher with no space in between the bricks. After this, the second layer of bricks is then arranged in columns with a gap in between two consecutive rows of bricks (Figure 7d). Although some brick makers prefer to leave a gap after each row of bricks. The spaces in between the rows of bricks are then filled with macadamia nut. The English bond pattern of brick arrangement is continued with allowance for macadamia nuts in every consecutive 5 to 6 layers of bricks (as shown in Figure 7e) until the desired height of clamp kiln is achieved. On attaining the desired height, an outer cover made up of two layers of bricks with a space of about 8 cm between the constructed structure and the outer layer is made round the kiln. Macadamia shells are then poured in this space after which it is covered with slanting placed bricks.

Laying of protective layer: This is done after the clamp kiln construction. The whole outer surface of the kiln is overlaid with previously fired and damaged dried bricks to conserve heat during firing process and then cemented with mortar [18]. In Vhembe district, laying of protective layer round the kiln is done gradually, and takes at least 2 days depending on the dimension of the kiln as well as the number of labourers involved. This process is commenced before ignition and completed after a handful amount of the fuel has been ignited. The mortar for plastering is prepared from a mixture of water and clay, initially stirred with shovel before kneading with the bare hand. Plastering is done with the bare hand. Conversely, the overlaying and plastering of the fire boxes are done after combustion have been initiated and fuel wood burning seriously.

Prior to sealing of the fire boxes, about 4 to 6 logs of wood are vertically erected at each entrance and around the fire boxes, one after the other. The protective layers of bricks are then arranged using the stretcher bond pattern (Figure 8a). The layers are simultaneously plastered using bare hand as they are being arranged (Figure 8b). The big fire boxes downwind are first sealed, leaving the opposite end for intermittent insertion of fuel wood (Figure 8c). By the time this is done, the kiln would have been fully ignited, the big fire boxes upwind are sealed up and the kiln allowed to burn.



(a) (b) (c) (d) (e) (f)

Figure 8. Firing Process. (**a**) Stretcher bond arrangement of the protective layer at the fire box; (**b**) Simultaneous plastering of the protective layers at the fire box; entrance; (**c**) Intermittent insertion of fuel wood; (**d**) Initiation of combustion in the clamp kiln; (**e**) Completely sealed clamp kiln; (**f**) Unfired (left) and fired dried (right) bricks.

Firing: This is also known as the combustion process in which fire is applied to the dried bricks within the clamp kiln. Firing of bricks in the IBMI in Vhembe District takes 2 to 4 days. On construction of the kiln, several logs of wood of different sizes and length are placed in the kiln through the fire boxes. After this quick flammable materials such as small pieces of wood, dry grasses and plastics are placed on top as well as in between the logs of wood at the entrance of the big fire boxes downwind. Combustion in the kiln is initiated at the fire boxes located in the wind direction. Initiation of ignition is carried out by striking the match on fast flammable materials such as dry grasses, plastic materials and crumps of wood placed at the entrance of the fire boxes (Figure 8d).

Once combustion is initiated at this end, the firing gradually gets transferred to the bigger logs of wood and is then conveyed to the other ends of the fire boxes. The transfer of fire and heat from one end of each fire boxes through the clamp kiln to the other end is enhanced by the wind. Logs of wood are supplied intermittently into the kiln through the big fire boxes. After about 5 to 6 h of burning, 4 to 6 long logs of fire wood are erected at the entrance of each fire boxes, and the entrance as well as the layers above the fire boxes sealed up with protective layers of bricks one after the other. This sealing process follows the following sequence: the big fire boxes downwind, all the small firing boxes then the big firing boxes upwind.

The kiln is completely sealed with protective layer at about 24 to 48 h after initiating the combustion (Figure 8e). The kiln is then allowed to combust for at least 2 days. At this stage temperature gets to the peak generating significant amount of smoke and heat from the top and walls of the kiln. In the process, fine and ultra-fine particulate matters [42], volatile aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylene isomers (BTEX) [43], carcinogenic substances such as Benzo[a]pyrene [44], polycyclic aromatic hydrocarbons hydroxylated metabolites of PAH (OH-PAHs) [45], butadiene, and formaldehyde [46] are also released. Exposure to PAH is associated with oxidative damage [47] and impairment of DNA resulting in the development of cancerous tumour especially in the airways [44]. Exposure to wood smoke induces increased systolic blood pressure and reduced heart rate response in older women [48].

Fine particulate matter ($PM_{2.5}$), on the other hand, penetrates deeply into lungs wreaking havoc based on its chemical composition and minute size [49]. Shaurya et al. [50] reported the association of lungs and cardiovascular infections, malfunctioning of pulmonary system and increased mortality rate with exposure to PM_1. Respiratory and cardiovascular symptoms such as sore throat, cough and high blood pressure were reported by some of the respondents. Heat related disorders like heat stroke, heat exhaustion, dehydration, heat syncope, heat cramps, and heat rash due to excessive exposure to heat are also associated with brick kiln workers [30]. Heat stress apparently raises the risk of injuries in the workshop and causes fatigue resulting in carelessness and loss of concentration [30].

When heating temperature gets to the peak, the dried bricks are transformed. Thereafter, the bricks get liquefied, expand then solidify as the temperature drops. Attributes such as tensile stress, resistance to thermal and mechanical stress are incorporated into the bricks during this transformation process. During this process, the initial greyish brown colour of the dried brick gradually changes to reddish brown (Figure 8f).

Cooling: This is a process which comes up immediately after the firing process is completed. At this stage virtually all the enveloped fuel wood or macadamia shell have been burnt to ashes. The lack of air and continuous fuel wood supply on sealing the whole kiln, initiate the formation of ash and final extinction of the ignited fire, consequently, the gradual drop in the kiln's temperature. Findings from the survey indicated that it takes an average of 3 days for cooling of fired bricks batch. Majority of the brick makers claimed that brick cooling takes 3 days. However, 5.3%, 13.2% and 28.9% agreed that cooling of brick takes less than 2 days, 1–2 days and more than 3 days, respectively.

De-hacking: This involves the unloading of the fired bricks from the kiln. De-hacking involves packing and dispatching of the bricks. On cooling, the enclosed kiln is uncovered to attract customers (Figure 9a). In Vhembe district, de-hacking of the fired bricks is done at the point of sale, fired bricks are dispatched with trucks (Figure 9b). Findings from our survey revealed that bricks are mostly transported to the point of use with the customers' trucks after sale. However, 15.8% of the respondents claim to own trucks which they use for conveying bricks to their respective customers.

(**a**) (**b**)

Figure 9. De-hacking Process (**a**) Uncovering of enclosed clamp kiln; (**b**) Dispatching of fired bricks with trucks.

Generally, de-hacking tends to be fast during wet seasons partly because of the reduced number of operational IBMI as well as higher demand for fired bricks for construction of houses. However, during dry season, de-hacking process could be slow, due to the existence of many operational local brick kilns. During this season, the price of bricks is usually competitive. The respondents claim to experience an average loss of 10%.

3.3. The Socio-Economic Conditions of the Traditional Brick Making Industry in Vhembe District

The socio-economic impacts of brick making deals with the direct and indirect employment opportunities associated with the brick making business, the status of the brick kiln workers, the operation modes of the industry, the impacts of brick making on the host community as well as challenges associated with the business.

To evaluate the socioeconomic state of the brick makers various parameters were considered in the present study, namely, nationality, gender, age, marital status, existence of co-workers, education, years of experience in brick making, distance of the residences from the brick yard, and sales prices of the produced bricks, monthly income of the workers in the study area.

The traditional Brick making industry has greatly influenced the socio-economic development of Vhembe district. The industry has helped in creation of jobs either directly or indirectly. The industry has been able to absorb some unemployed indigenes and migrants as brick makers working in the various sections of the brick manufacturing processes. Findings from the survey indicated that 13.2% of the total respondents from the two villages understudied are South Africans while Zimbweans (76.3%) and Mozambicans (10.5%) made up the remainder of the workers. Maithel et al. [8] and Lundgren-Kownack et al. [51] in their respective studies in India, stated that larger percentage of the work force are migrants who work at the brick kilns in non-monsoonal season and in the agrarian sector during the rainy season. Our finding is similar to the outcome of the study conducted by [15] in which the influx of migrant brick makers from the neighbouring countries into the northern parts of South Africa especially in Limpopo Province, was observed.

Unlike in Manini where all the respondents are Zimbabweans, the brick makers in Tshilungoma are conglomerate of 3 nationalities: Mozambique, South Africa and Zimbabwe. The survey revealed that majority (71.1%) of the total respondents from the two villages understudied, are labourers either employed by managers (usually South Africans) or working on their own on leased pieces of land. In most cases, certain percentage of the profit made on the sales of fired bricks is paid either per fired batch of bricks or annually to the landowners. However, 28.9% of the respondents are managers either working alone or with co-workers. All the South African brick makers interviewed are managers and landowners.

The demographical analysis of the survey showed that majority (65.8%) of the brick makers are male while female account for 34.2% of the respondents (Table 4). This observation correlates with findings from similar studies carried out in Bangladesh and India. Das et al. [28] in Bangladesh, claimed that majority (66.92%) of the brick kiln workers were male. Similarly, Sanjel et al. [30] in their study in India also found that 75.4% of the brick makers are male. The low proportion of female could be partly due to the tedious nature of the job. The age groups of the respondents span between less than 18 years and above 57 years. In addition, the study showed that 60.5% of the respondents were married, and 39.5% were un-married. In total, 60.9% of the married brick workers were couples working together with or without other co-workers. Brick making in Africa, Asia and some other parts of the world are known to be family-owned cottage business [1].

Table 4. Comparison of the Socio-economic parameters of Brick makers in Vhembe District with Similar studies.

	This Study (n = 38)	Kazi and Bote, [29]	Das et al., [28]	Sanjel et al., [30]
Gender				
Male	65.8	44.3	66.92	74.5
Female	34.2	55.7	33.08	25.5
Total	100.0	100.0	100.0	100.0
Marital status				
Married	60.5	**NR**	90.05	**NR**
Single	39.5	**NR**	9.95	
Total	100.0	**NR**	100.0	
Education				
Illiterate			9.70	
Primary School	47.4	**NR**	72.64	63.0
Secondary School	50.0	**NR**	17.66	35.1
Tertiary	2.6	**NR**		1.9
Total	100.0		100.0	100.0
Monthly income for majority of the brick workers	(105.13–420.52) USD.	**NR**	(117.91–235.82) USD	**NR**

NR: Not reported.

Since traditional brick making is an unskilled craft requiring no special qualification, survey has shown that a half of the brick makers had secondary education while 47.4% and 2.6% of the respondents had primary and above secondary education, respectively. Abdalla [52] in a similar study in Sudan, observed that all of the brick makers had below University education. Das et al. [28] likewise observed that none of the respondents in a similar study in Bangladesh had above Secondary education. Kazi and Bote [29] reported that brick making is a low paying job requiring no skill. Based on work experience in brick making, 28.9%, 34.2%, 13.2%, 5.3% and 18.4% were associated with experience levels of less than 1 year, 1–3 years, 4–6 years, 7–9 years and above 9 years respectively. Results from this survey correlates with those of Sanjel et al., [30], in which over 70% of the brick makers had working experience of 10 years and below, in brick making.

Generally, 2.6% of the interviewed brick makers reside on the brick site while 2.6%, 18.4%, 50%, 21.1% and 5.3% of the respondents stay at distances below 200 m, 200 m–500 m, 500 m–2 km, 2.1 km–5.0 km and above 5 km from their respective work place. This finding is in congruent with the report obtained from similar study in Nepal where most brick makers with their households reside in inadequately ventilated buildings constructed on the brick site [49].

Further investigation revealed the distribution of co-workers of the respondents in the various industries visited to be between 0 and 9. This means that the number of labourers working in each brick site ranges from 1 to 10. Unlike in Manini where 75% of its respondents work with two other colleagues, 50% of the participants in Tshilungoma village, work in pairs. There is no specialisation in the informal brick making setting, all the brick makers are involved in every stage of the brick production. All the workers perform the same task together per time. This study also shows that most of the brick makers in Tshilungoma are couples with or without other co-workers. However, many of the brick makers in Manini are unmarried between 18 and 27 years and most of the few married ones work without their spouses.

The industry has also influenced the economic growth of the district in terms of construction of buildings. Bricks are sold by the industry to the local communities at affordable prices. Generally, the price per brick from the local brick making sector in Vhembe district is R1.00 (0.07 USD), however 40% of the respondents argued that the price varies with season. In all, 2.9% and 31.4% of the respondents said brick price during winter, fluctuates between R0.5 and 0.69 and R0.7 and 0.99, respectively. Conversely, summer brick prices of R0.7–0.99 and R1.01–1.20 were claimed by 5.3% and 13.2% of the respondents respectively.

Brick making is a low-income job [18]; however, it has helped in reducing the rate of unemployment in Vhembe District. Findings from this survey has shown the monthly income of the local brick yard workers spanning between R1500 (105.13 USD) and R6000 (420.52 USD). This finding is in congruent with the range of monthly income of 117.91–235.82 USD for most brick kiln workers in Bangladesh [28]. Cermalab, [18] stated that the wages earned by brick kiln workers might be lower than the minimum income.

Furthermore, the operation of the brick kiln has provided other related jobs such as the sales and repair of brick making tools, sales and transportation of fuel, as well as construction of buildings amongst others. The industry also provides indirect sources of employment to brick suppliers and transporters, builders, welders and carpenters [53]. The industry enhances the economic growth of its locality and supplies bricks at affordable prices to the host community and its suburbs.

The detrimental social impacts of the industry include loss of fertile topsoil resulting in the infertility of the surrounding farmlands, lower water holding capacity of the soil and consequently reduced crop yield [19,53]. In addition, roads leading to the brick yards often contain potholes which may be partly due to the heavy trucks transporting bricks that are plying the road [53]. Other socio-economic impacts of brick making industry include deforestation, competition with other walling industries and water lodging [11,31,34]. Challenges encountered by the brick maker include poor wages, lack of medical care, unavailability of ablution facilities, absence of education for their children and unavailability of potable water [18,28,29,53].

3.4. Environmental Implications of Brick Making

Brick making around the world has been highlighted as having many and significant detrimental environmental impacts [3,17,54,55]. These impacts include deterioration of air quality, climate change, human health effects, impacts on vegetation, loss of soil fertility [2,8,14,20,30,34,49,50], deterioration of animal life, heritage sites, sculptures and metallic structures [2,3,8,20,36]. Emissions to the atmosphere and impacts on air quality is certainly one of the larger impacts from this industry and will be discussed in detail in this section.

Atmospheric emission is a major problem with the informal brick making industry due to the crude technology, the processes and the fuel sources [12,34]. Pollutants are often emitted through the stack-less kiln at low height, into the atmosphere [3,12,49]. The fumes gases generated spontaneously diffuse and disperse rapidly to the ground [56], thus increasing the ground level concentration of the pollutants. Air pollutants such as CO, CO_2, SO_2, particulate matters [3], NOx [2], NO [20], Black Carbon [8], volatile organic compounds (VOC) [27], metals, tropospheric ozone (O_3) and total organic compounds (TOC) [13,14] are generated from brick making processes. The various phases of brick making drive different emissions and the impacts are variable. The two major stages of production that generate air pollutants in the traditional brick making industries are the excavation and firing stages. Fugitive emissions, majorly PM10 are associated with excavation [54,57]. However, majority of the gaseous and particulate pollutants generated from brick making are released during brick firing [12].

The air pollutants result in poor air quality which in turn drives impacts on human health. People residing close to the brick industry are the most likely to be impacted. The host communities, especially the local workers [3,8,12,49] with their children [56] are more prone to the adverse health impacts, since they are exposed to elevated levels of pollutants for extended period of time [35]. Table 5 shows the health challenges associated with the traditional brick kiln workers. The pollutant with the highest direct impact is particulate matters, owing to the varying chemical composition and physical characteristics [57].

PM10 and PM2.5 include respirable aerosol that are very tiny, having high potential to penetrate the thoracic region of the respiratory system. PM2.5 is a more hazardous than the coarse part of PM10 [58]. Fine and ultra-fine particulate matters in the inhaled air infiltrate through the lungs, entering the circulatory system, then dissolve and could be transported to distant organ or tissue of the body, undergoing chemical transformation and forming new chemicals which cause several deleterious effects [49,50,59]. Exposure to particulate matter (PM) has been linked to lung inflammatory reactions, cardiopulmonary infections such as intravascular thrombin formation, ischemic heart disease, cerebrovascular infection, cardiac dysrhythmias, congestive heart failure, and stroke [60].

Similarly, carbon monoxide (CO) released from incomplete combustion of fuel during brick firing, increases risk for heart diseases [19]. Sulfuric acid (H_2SO_4), SO_2 and sulfate salts tend to irritate the mucous membrane of the respiratory track resulting in the development of chronic respiratory infections, such as bronchitis, pulmonary emphysema and asthma [20,61–63]. Other health disorders common among brick kiln operators include gastrointestinal problem, ear and eye disorders [28], as well as musculoskeletal pains [61,63,64] as shown in Table 6.

Table 5. Health challenges associated with brick kiln workers.

Studies	**Mukwevho et al. [61] (*n* = 580)**	**Das et al. [28] (*n* = 402)**	**Shaikh et al. [62] (*n* = 340)**	**Sanjel et al. [30] (*n* = 400)**
Location (Country)	Limpopo, South Africa	Bangladesh	Pakistan	Kathmandu valley, Nepal
		Respiratory problem		
Chest pain/Respiratory distress	54.7%	31.8	NR	NR
Chronic cough	NR	17.2	22.4	14.3
Phlegm	NR	NR	21.2	16.6
Shortness of breath with wheezing	NR	NR	13.8	11.3
Bronchitis	NR	NR	17.1	19.0
Asthma	NR	NR	8.2	6.3

NR: Not reported.

Table 6. Musculoskeletal health disorders associated with brick kiln workers.

Studies	**Mukwevho et al. [61]**	**Joshi et al. [63]**		**Inbaraj et al. [64]**
Location (Country)	Limpopo, South Africa (*n* = 580)	Bhaktapur, Nepal (*n* = 73)	Sarlahi, Nepal (*n* = 49)	Southern India (*n* = 310)
		Musculoskeletal pain		
Neck	97.8	52.1	44.9	11.3
Shoulder	59.7	42.5	19.6	23.5
Elbow	NR	34.2	33.1	20.6
Wrist/Fingers	54.1	38.4	34.2	13.9
Upper back	65.2	54.8	8.2	8.7
Lower back	55.8	54.8	10.2	59
Hips	59.7	50.7	41.7	20.6
Knee	NR	60.3	57.9	44.8
Ankle	NR	68.2	69.2	22.9

NR: Not reported.

Emissions from brick kilns also influence the plants and non-living substances in the environment. Acid deposition from SO_2 released from flue gas generated by brick kilns reacts with water and rain and increases soil acidity resulting in yellowing of crops, growth retardation, hence reducing crop quality and yield [36,65]. Emissions from brick kilns when released fall on the flora within the host community. They block the stomata hindering photosynthetic as well as respiratory processes, increase physical injury and metal concentrations in crop grains [65]. In addition, heat generated from the kiln causes nutrient destruction which alters the physicochemical properties as well as of the soil and biodiversity of floral communities [11,66]. In addition, $PM_{2.5}$ impact on visibility and climate, due to its long atmospheric retention time [8].

3.5. Influence of Brick making on Climate Change

In addition to air pollutants released from brick making, is the generation of Greenhouse gases (GHGs), mainly from combustion of fossil fuel. Significant release of GHGs such as carbon dioxide, nitrogen oxides (NO_x), nitrous oxide (N_2O), nitric oxide (NO) and methane are partly responsible for the unusual changes in climatic condition [34,35,39]. Globally, about 70% of total GHG emissions are attributable to the burning of fossil fuel from the industrial sectors [37]. On a similar note, South Africa was announced as the 14th chief emitter of GHGs [67]. In 2016, the global annual emission report indicated CO_2 as the key player in global emission contributing 74.4% of total emissions. Other GHGs namely: methane, nitrous oxide and fluorinated compounds accounted for 17.3%, 6.2% and 2.1%, respectively [68].

The continual increase in anthropogenic emissions of GHGs, as it is currently being experienced, is dynamically modifying the climatic conditions, both at the international and local level [69]. Today, climate change is becoming a global issue, owing to its increasing multifaceted and interconnected adverse effects [39,70]. The effects of climate change on meteorological processes and environmental events are well documented [38]. The extreme weather events such as water scarcity, severe drought, elevated precipitation and tropical cyclones, result in increased instability in food production in many localities [51]. These effects become progressively intense, prompting injuries, serious communicable diseases and mortalities [37,38].

3.6. SWOT Analysis of the Traditional BMI

A SWOT analysis is a framework which evaluates the internal and external environments of an organization so as to pinpoints the strengths, weaknesses, opportunities and threats encountered by the organization [71]. For effective operation of the traditional BMI, it is highly essential that the industry leverages its strength, lessen the threats and make best use of the opportunities. Below is the SWOT analysis of the traditional BMI (Figure 10). The major weaknesses of traditional BMI include the removal of topsoil meant for agricultural purpose, the falling of trees and the release of gaseous and particulate emissions into the atmosphere. All these weaknesses result in the degradation of the environment. Bricks could be manufactured in a more sustainable way through the incorporation of industrial and agricultural wastes such as dry water treatment sludge, thermal plant bottom ash, mining tailings, fly ash, rice husk ash, sugarcane bagasse ash into the clay mixture. This green method of brick production embraces recycling of waste, thus reducing the extent of soil exploitation and use of fuelwood. Since air pollutants emissions in brick making processes are mostly generated from the combustion of fuel, the reduction of the amount of fuel used, therefore could bring about reduction in air pollution. In addition, the use of alternative cost-effective technique can be employed.

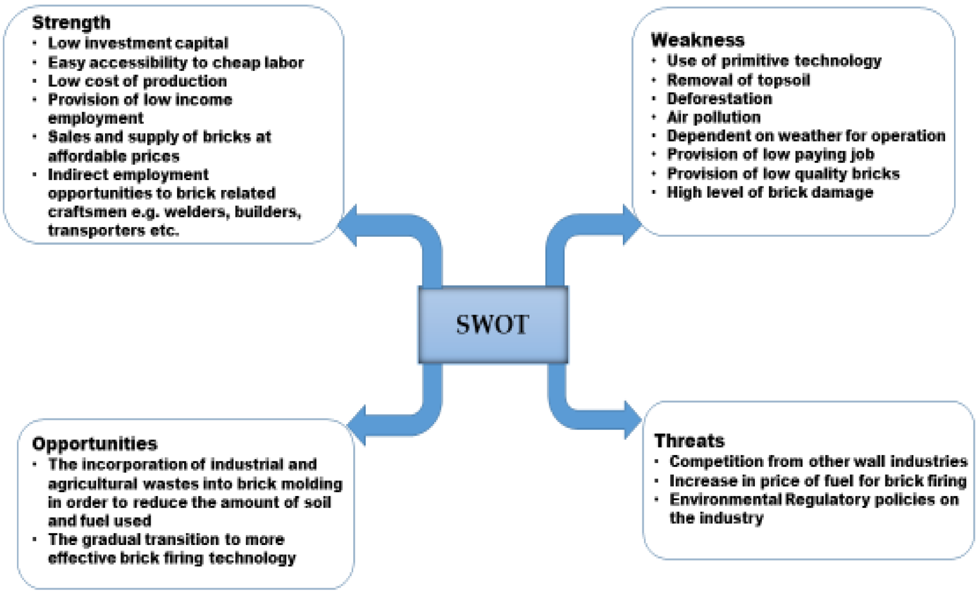


Figure 10. SWOT analysis of the traditional BMI.

Additionally, the gradual transition from traditional method of brickfiring to a more efficient brickfiring technology is essential to foster a sustainable environment. A modern brick making technology such as the Vertical Shaft Brick Kiln (VSBK) which accommodates the traditional method of brick moulding could be employed for a start pending the full automation of the modern technology. The establishment of a community owned energy efficient kiln such as the VSBK, in which local brick makers can bring in their own moulded bricks for firing would go a long way in reducing air pollutants emissions. Furthermore, it would be helpful if co-operative societies could be established, to strengthen the means of operation adopted by brick makers. This would, in turn, increase the overall financial output.

3.7. VSBK: An Environmentally Sustainable Technology for Brick Firing

There are several brick making techniques used in South Africa, however, the Vertical Shaft Brick Kiln (VSBK) is the predominantly used modern technology for brick making in Vhembe District, due to its high efficiency, energy saving and environmentally friendly attributes relative to other modern technologies. To this effect, we determined the energy efficiency of the VSBK by comparing the energy utilised in the combustion of 1000 bricks by the VSBK and the clamp kiln.

In all, 303 kg and 68 kg of wood and coal, equivalent to 5393.4 MJ and 2109.2 MJ of energy were used for the combustion of 1000 bricks in the clamp kiln and VSBK, respectively. This resulted in 61% reduction in fuel consumption as shown in Table 7. De Giovanetti and Volsteedt [72] claimed energy reduction of 30–50% through the replacement of clamp kiln with VSBK. On the other hand, Maithel and Heierli [1], and Erbe [73] reported over 60% and 70% energy reduction per kilogram of fired bricks, respectively, with the use of VSBK technology over clamp kilns. These results [1,72,73] are comparable with the 61% energy reduction attained in this study.

Table 7. Comparison between fuel consumption per 1000 bricks with the use of clamp kiln and VSBK. technologies in Vhembe District.

Technology	Fuel Consumed per 1000 Bricks (kg)	Energy Content of Fuel Used per 1000 Bricks (MJ)	% Reduction in Fuel Consumption
Clamp	303	5393.4	
VSBK	68.0	2109.2	61%

In addition, the advantages of the VSBK over the clamp kiln technology, in terms of the technique, space utilised, firing cycle and monthly production capacity, obtainable in Vhembe District are presented (Table 8).

Table 8. The merits of VSBK over the Clamp kiln technology.

		Clamp	VSBK
1	**Technique**	Temporary structure, crude, batched, seasonal, no chimney	Mechanised, fixed structure, operates all through the year, presence of chimney
2	**Space Utilization**	Large	Small
3	**Firing cycle**	48–96 h	22–24 h
4	**Monthly production**	About 36,000 bricks per kiln	About 0.82 million bricks ≈ 23 times of clamp kiln production

4. Limitation of the Study

Small sample size was used for this study because many of the brick makers were scared of been reported and participation was voluntary, if a larger size was used a better result would have been obtained. Additionally, due to fear of apparent repercussions from law enforcement agents, brick makers could have also presented bias information as they may not be truthful in responding to some questions during the data collection. In addition, likely pollutants emitted in the various phases of brick production were stated based on data from reviewed literatures, but the emitted pollutants were not identified and measured during the course of this study. It is therefore recommended that further studies to quantify emissions around the informal brick kilns and to evaluate the levels of exposure of the local communities to atmospheric emissions be conducted in the future.

5. Conclusion

The use of locally available materials such as clay from a river bed, firewood from a nearby forest or waste product from agriculture makes the brick making process cheap and contributes positively to the socioeconomic status of the brick makers. However, the low-cost firing technique contributes to emissions that are detrimental to the health of the brick workers and the environment. The green method of brick production which entail the recycling of industrial and agricultural wastes would enhance the development of a sustainable environment. Additionally, the gradual transition from traditional techniques of brick firing to an environmentally friendly technology is a necessity. The establishment of a community owned energy efficient kiln such as the VSBK, serving as a source of employment for local brick maker would go a long way in reducing emissions associated with brick making.

Author Contributions: Conceptualization, T.E.A., J.N.E. and J.O.O.; methodology, T.E.A., J.N.E. and J.O.O.; software, J.N.E. and J.O.O.; validation, J.N.E., J.O.O. and S.J.P.; formal analysis, T.E.A.; investigation, T.E.A.; resources, J.O.O.; data curation, T.E.A.; writing—original draft preparation, T.E.A.; writing—review and editing, J.N.E., J.O.O. and S.J.P.; visualization, T.E.A.; supervision, J.N.E. and J.O.O.; project administration, J.O.O.; funding acquisition, J.O.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by ESKOM, grant number E349 and Eskom Power Plant Engineering Institute (EPPEI).

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by Research and Ethics Committee of the University of Venda (Project Number: SES/19/ERM/08/1309 and Date of Approval: 13 Sepmtember 2019).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study would be made available by the corresponding author on request.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Maithel, S.; Heierli, U. *Brick by Brick: The Herculean Task of Cleaning up the Asian Industry*, 1st ed.; Osborn, P., Ed.; Swiss Agency for Development and Cooperation (SDC), Natural Resource and Environmental Division: Berne, Switzerland, 2008; pp. 1–132.
2. Hoque, H.M.A.; Ahmed, Z.; Islam, S.M.A.; Saha, G.C.; Osman, M.S. Pollution scenario of Brick Industry and way forward. In *Proceedings of International Conference on Industrial Waste Management and Process Efficiency*; Department of Civil Engineering, DUET: Gazipur, Bangladesh, 2012; pp. 154–161.
3. Uma, R.; Athalye, V.; Ragavan, S.; Mathiel, S.; Lalchandani, D.; Kumar, S.; Baum, E.; Weyant, C.; Bond, T. Assessment of air pollutant emission from brick kilns. *Atoms Environ.* **2014**, *98*, 549–553.
4. Ngcofe, L.; Cole, D.I. The distribution of the economic mineral resource potential in the Western Cape Province. *S. Afr. J. Sci.* **2014**, *110*, 1–4. [CrossRef]
5. Hashemi, A.; Cruickshank, H. Embodied Energy of Fired Bricks: The Case of Uganda and Tanzania. In Proceedings of the 14th International Conference on Sustainable Energy Technologies (SET 2015), Nottingham, UK, 25–27 August 2015; pp. 1–8.
6. Dalkilic, N.; Nabikoglu, A. Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). *Front. Archit. Res.* **2017**, *6*, 346–359. [CrossRef]
7. Rice, G.A.; Vosloo, P.T. A life cycle assessment of the cradle-to-gate phases of clay brick production in South Africa. *Eco-Archit. V Harmon. Archit. Nat.* **2014**, *142*, 474. [CrossRef]
8. Maithel, S.; Lalchandani, D.; Malhotra, G.; Bhanware, P.; Uma, R.; Ragavan, S.; Athalye, V.; Bindiya, K.R.; Reddy, S.; Bond, T.; et al. Monitoring of brick kilns and strategies for cleaner brick production in India. In *Brick kiln Performance Assessment and a Roadmap Cleaner Brick Production in India*, Revised ed.; A Shakti Sustainable, Energy Foundation Supported Initiative; Shakti Sustainable Energy Foundation and Climate Works Foundation: New Delhi, India, 2012; pp. 1–21.
9. Corporación Ambiental Empresarial (CAEM). Analysis of technological models used in South Africa. In *Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants*; Mission of South Africa, Corporación Ambiental Empresarial: Gauteng, South Africa, 2016; pp. 1–18.
10. Bates, C.N. Feasibility Evaluation of Fired Brick Technology as a Construction Material and Income-Generating Industry in Northern Ghana. Master's Thesis, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA, 2014.
11. Alam, S.A. Use of Biomass Fuels in the Brick Making Industries of Sudan: Implications for Deforestation and Greenhouse Gas Emission. Master's Thesis, Department of Forest Ecology, University of Helsinki, Helsinki, Finland, 2006; pp. 16–17.
12. Kanabkaew, T.; Buasing, K. Assessment of air pollution concentrations from brick kilns using an atmospheric dispersion model. *Ecol. Environ.* **2015**, *198*, 27–37.
13. Akinshipe, B.O. Atmospheric Emissions and Energy Metrics from Simulated Clamp Kiln Technology in the South African Clay Brick Industry. Ph.D. Thesis, Department of Chemical Engineering, Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Pretoria, South Africa, 2017.
14. Akinshipe, O.; Kornelius, G. Quantification of atmospheric emissions and energy metrics from simulated clamp kiln technology in the clay brick industry. *J. Environ. Pol.* **2018**, *236*, 580–590. [CrossRef] [PubMed]
15. Swiss Contact and Clay Brick Association of South Africa. *SADC Countries-Clay Brick Production Survey*; Swiss Contact Report; Swiss Contact and Clay Brick Association of South Africa: Pretoria, South Africa, 2017; pp. 1–36. Available online: www.swisscontact.org (accessed on 20 November 2020).
16. Twala, N.S. *Overview of South Africa's Clay Brick Industry*; Directorate: Mineral Economics; Report R73/2008; Mineral Resources Republic of South Africa: Pretoria, South Africa, 2008.
17. Weyant, C.; Kumar, S.; Maithel, S.; Thompson, R.; Baum, E.; Floess, E.; Bond, T. *Brick Kiln Measurement Guidelines: Emissions and Energy Performance*; University of Illinois, Urbana-Champaign Civil and Environmental Engineering and Greentech Knowledge Solutions Pvt. Ltd.: Champaign, IL, USA, 2016.
18. Cermalab, CC. *Survey of the Status of the Informal Clay Brick Making Sector Eastern Cape, South Africa*; Cermalab CC: Pretoria, South Africa, 2014; pp. 1–83.
19. Jerin, M.F.; Mondol, S.K.; Sarker, B.C.; Rimi, R.H.; Aktar, S. Impacts of brick fields on environment and socio-economy at Bagatipara, Natore, Bangladesh. *J. Environ. Sci. Nat. Resour.* **2016**, *9*, 31–34. [CrossRef]
20. Darain, K.M.; Rahman, A.B.M.S.; Ahsan, A.; Islam, A.B.M.S.; Yusuf, B. Brick manufacturing practice in Bangladesh: A review of Energy Efficacy and Air Pollution Scenarios. *J. Hydrol. Environ. Res.* **2013**, *1*, 60–69.
21. Littlejohn, A. Who Invented Bricks, Mortar, and Concrete? *Owlcation*, 5 March 2019.
22. Aurangzeb, K.; Carsten, L. Bricks and Urbanism in the Indus valley rise and decline. *Am. J. Arch.* **2013**, *1*, 1–13.
23. Mason, T.O.; Lee, J.A. Brick and tile (building material). *Encyclopaedia Britannica*, 24 May 2019.
24. Emery, V.L. Mud-brick architecture. *UCLA Encycl. Egyptol.* **2019**, *1*, 1–14.
25. Jackson, M. The building blocks: A brief history of brick. *The Journal of the American. Institute of Architects Magazine*, 1 March 2018.

26. National School of Government (NSG). Republic of South Africa, Municipalities of South Africa. 2018. Available online: https://municipalities.co.za/overview/129/vhembe-district-municipality (accessed on 30 August 2019).
27. Modiselle, M. *Special Clays Industry in the Republic of South Africa, Directorate: Mineral Economics*; Report R80/2009; Department of Mineral Resources: Pretoria, South Africa, 2009; pp. 1–35.
28. Das, S.; Hasan, M.S.Q.; Akhter, R.; Huque, S.; Khandaker, S.; Gorapi1, M.Z.H.; Shahriar, M. Socioeconomic conditions and health hazards of brick field workers: A case study of Mymensingh brick industrial area of Bangladesh. *J. Public Health Epidemiol.* **2017**, *9*, 198–205. [CrossRef]
29. Kazi, R.N.; Bote, M.M. A cross sectional study to determine the health profile of brick kiln workers. *Int. J. Community Med. Public Health* **2019**, *6*, 5135–5141. [CrossRef]
30. Sanjel, S.; Khanal, S.N.; Thygerson, S.M.; Carter, W.S.; Johnston, J.D.; Joshi, S.K. Respiratory symptoms and illnesses related to the concentration of airborne particulate matter among brick kiln workers in Kathmandu valley, Nepal. *Ann. Occup. Environ. Med.* **2017**, *29*, 1–12. [CrossRef] [PubMed]
31. Mazumdar, M.; Goswami, H.; Debnat, A. Brick Industry as a source of pollution-Its Causes and impacts on human rights: A Case Study of Brick Kilns of Palasbari Revenue Circle. *Int. J. Humanit. Soc. Sci.* **2018**, *6*, 220–240.
32. Islam, N.; Roy, R. Problem of water loging through soil quarrying in Brick kiln industry: A study of Tufanganj Block-I, Koch Bihar, West Bengal. *Int. J. Theor. Appl. Sci.* **2017**, *9*, 192–200.
33. Nazari, S.; Kermani, M.; Fazlzadeh, M.; Alizadeh-Matboo, S.; Yari, A.R. The origins and sources of dust particles, their effects on environment and health, and control strategies: A review. *J. Air Pollut. Health* **2016**, *1*, 137–152.
34. Shakir, A.; Mohammed, A.A. Manufacturing of bricks in the past, in the present and in the future: A state of the Art Review. *Int. J. Adv. Appl. Sci. IJAAS* **2013**, *2*, 145–156. [CrossRef]
35. Lalchandani, D.; Maithel, S. *Towards Cleaner Brick Kilns in India A win–win approach based on Zigzag firing technology, Greentech Knowledge Solutions Pvt. Ltd., A Shakti Sustainable Energy Foundation Supported Initiative*; ADCS (Academic and Development Communication Services): Chennai, India, 2013; pp. 1–21.
36. Ahmed, S.; Hossain, I. Applicability of air pollution modeling in a cluster of brickfields in Bangladesh. *Chem. Eng. Res. Bull.* **2008**, *12*, 28–34. [CrossRef]
37. The Lancet Commissions. Health and Climate Change: Policy Responses to Protect Public Health. Published online 23 June 2015. Available online: http://dx.doi.org/10.1016/S0140-6736(15)60854-6.
38. Hashim, J.H.; Hashim, Z. Climate Change, Extreme Weather Events, and Human Health Implications in the Asia Pacific Region. *Asia Pac. J. Public Health* **2016**, *28*, 8S–14S. [CrossRef]
39. Olaleru, S.A.; Kirui, J.K.; Elegbeleye, F.I.; Aniyikaiye, T.E. Green technology: Solution to global climate change mitigation. *Energy Environ. Storage.* **2021**, *1*, 26–41. [CrossRef]
40. Bada, S.O.; Falcon, R.M.S.; Falcon, L.M.; Makhula, M.J. Thermogravimetric investigation of macadamia nutshell, coal, and anthracite in different combustion atmospheres. *J. S. Afr. Inst. Min. Metall.* **2015**, *115*, 741–746. [CrossRef]
41. Diez, H.E.; Perez, J.F. Physicochemical Characterization of representative firewood species used for cooking in some Colombian Regions. *Int. J. Chem. Eng.* **2017**, *2017*, 4531686. [CrossRef]
42. Li, Z.; Trinidad, D.; Pittman, E.N.; Riley, E.A.; Sjodin, A.; Dills, R.L.; Paulsen, M.; Simpson, C.D. Urinary polycyclic aromatic hydrocarbon metabolites as biomarkers to wood smoke exposure—Results from a controlled exposure study. *J. Exposure Sci. Environ. Epidemiol.* **2016**, *26*, 241–248. [CrossRef] [PubMed]
43. Piccardo, M.T.; Cipolla, M.; Stella, A.; Ceppi, M.; Bruzzone, M.; Izzotti, A.; Valerio, F. Indoor pollution and burning practices in wood stove management. *J. Air Waste Manag. Assoc.* **2014**, *64*, 1309–1316. [CrossRef]
44. National Institute for Public Health and the Environment Ministry of Health, Welfare and Sport, NIPHEMH—Netherlands 2018, Benzo[a]pyrene (BaP). Available online: https://www.rivm.nl/en/tobacco/harmful-substances-in-tobacco-smoke/benzo-a-pyrene-bap (accessed on 31 December 2020).
45. Adetona, O.; Simpson, C.D.; Li, Z.; Sjodin, A.; Calafat, A.M.; Naeher, L.P. Hydroxylated polycyclic aromatic hydrocarbons as biomarkers of exposure to wood smoke in wildland firefighters. *J. Exposure Sci. Environ. Epidemiol.* **2017**, *27*, 78–83. [CrossRef]
46. Sallsten, G.; Gustafson, P.; Johansson, L.; Johannesson, S.; Molnar, P.; Strandberg, B.; Tullin, C.; Barregard, L. Experimental Wood Smoke exposure in humans. *J. Inhal. Toxicol.* **2006**, *18*, 855–864. [CrossRef] [PubMed]
47. Abreu, A.; Costa, C.; Pinho e Silva, S.; Morais, S.; Carmo Pereira, M.; Fernandes, A.; De Andrade, V.M.; Teixeira, J.P.; Costa, S. Wood smoke exposure of Portuguese wildland firefighters: DNA and oxidative damage evaluation. *J. Toxicol. Environ. Health* **2017**, *80*, 596–604. [CrossRef]
48. Khaing, P.; Mazumder, S.; Dube, B.; Taneja, S.; Yan, B.; Chillrud, S.; Bhandari, N.; D'armiento, J.; Lee, A. C60 Indoor Air Pollutants: Biomass and Wood Smoke: Cardiovascular health effects of dung biomass smoke exposure: Effect modification by age. *Am. J. Respir. Crit. Care Med.* **2017**, *195*, A5983.
49. Thygerson, S.M.; Beard, J.D.; House, M.J.; Smith, R.L.; Burbidge, H.C.; Andrus, K.N.; Weber, F.X.; Chartier, R.; Johnston, J.D. Air-Quality Assessment of On-Site Brick-Kiln Worker Housing in Bhaktapur, Nepal: Chemical Speciation of Indoor and Outdoor PM2.5 Pollution. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4114. [CrossRef]
50. Johari, S.; Goel, I.; Mandal, A. Health effects of ultrafine particles (PM1.0): A review. *Mater. Sci.* **2017**, *3*, 1–10.

51. Lundgren-Kownacki, K.; Kjellberg, S.M.; Gooch, P.; Dabaieh, M.; Anandh, L.; Venugopal., V. Climate change-induced heat risks for migrant populations working at brick kilns in India: A transdisciplinary approach. *Int. J. Biometeorol.* **2018**, *62*, 347–358. [CrossRef]
52. Abdalla, I.M.F. Environmental Impact of Red Brick Manufacturing on the Bank of the Blue Nile at Soba West, Khartoum, Sudan. *Int. J. Curr. Microbiol. Appl. Sci.* **2015**, *4*, 800–804.
53. Bhattacharya, M. Physical and Socio-Economic Environmental Consequences of Brick Industry: A Case Study of Domohani Village. *J. Adv. Sch. Res Allied Educ.* **2018**, *15*, 192–197. [CrossRef]
54. Corral-Avitia, A.Y.; Mora-Covarrubias, A. Environmental Assessment of Brick Kilns in Chihuahua State, México, Using Digital Cartography. *Funct. Ecosyst.* **2012**, *14*, 261–282.
55. Nepal, S.; Mahapatra, P.S.; Adhikari, S.; Shrestha, S.; Sharma, P.; Shrestha, K.L.; Pradhan, B.B.; Puppala, S.P. A Comparative Study of Stack Emissions from Straight-Line and Zigzag Brick Kilns in Nepal. *Atmosphere* **2019**, *10*, 107. [CrossRef]
56. Bellprat, O. *Brick Kiln Evaluation Study in the Bajıo Region GTO, Mexico*; Institute Nacional de Ecological, Eidgenossische Technische Hochschule Zurich, Swiss Federal Institute of Technology: Zurich, Switzerland, 2009; pp. 1–31.
57. The Ministry for the Environment, New Zealand. *Good Practice Guide for Assessing and Managing Dust*; Ministry for the Environment, Manatu Mo Te Taiao: Wellington, New Zealand, 2016; pp. 1–78.
58. World Health Organisation, Europe. *Health Effects of Particulate Matter, Policy Implications for Countries in Eastern Europe, Caucasus and Central Asia*; WHO Regional Office for Europe UN City: Copenhagen, Denmark, 2013; pp. 1–15.
59. Tan, Z. *Air Pollution and Greenhouse Gases. Green Energy and Technology*; Springer Science+ Business Media: Singapore, 2014. [CrossRef]
60. Wu, W.; Jin, Y.; Carlsten, C. Inflammatory health effects of indoor and outdoor particulate matter. *J. Am. Acad. Allergy Asthma Immunol.* **2018**, *141*, 833–844. [CrossRef]
61. Mukwevho, M.H.; Zikhali, P.T.S.; Radzilani-Makatu, M. Effect of employees' working conditions in the burnt brick manufacturing industries in the Vhembe District of Limpopo Province, South Africa. *Afr. J. Phys. Health Educ. Recreat. Danc.* **2014**, *20*, 481–490.
62. Shaikh, S.; Nafees, A.A.; Khetpal, V.; Jamali, A.A.; Arain, A.M.; Yousuf, A. Respiratory symptoms and illnesses among brick kiln workers: A cross sectional study from rural districts of Pakistan. *BMC Public Health* **2012**, *12*, 999. [CrossRef]
63. Joshi, S.K.; Dahal, P.; Poudel, A.; Sherpa, H. Work related injuries and musculoskeletal disorders among child workers in the brick kilns of Nepal, International. *J. Occup. Saf. Health* **2013**, *3*, 2–7. [CrossRef]
64. Inbaraj, L.R.; Haebar, O.J.; Saj, F.; Dawson, S.; Paul, P.; Prabhakar, A.P.; Mohan, V.R.; Alex, R.G. Prevalence of musculoskeletal disorders among brick kiln workers in rural Southern India. *Indian J. Occup. Environ. Med.* **2013**, *17*, 71–75.
65. Adrees, M.; Ibrahim, M.; Shah, A.M.; Abbas, F.; Saleem, F.; Rizwan, M.; Hina, S.; Jabeen, F.; Ali, S. Gaseous pollutants from brick kiln industry decreased the growth, photosynthesis, and yield of wheat (*Triticum aestivum* L.). *Environ. Monit. Assess.* **2016**, *188*, 267. [CrossRef] [PubMed]
66. Gupta, S.; Narayan, R. Brick kiln industry in long-term impacts biomass and diversity structure of plant communities. *Curr. Sci.* **2010**, *99*, 72–79.
67. Carbon Brief's Country Profile: South Africa. South Africa's Heavy Dependence on Coal and Expanding Effort to Develop Renewables. 2018. Available online: https://www.carbonbrief.org/the-carbon-brief-profile-south-africa (accessed on 4 June 2021).
68. Ritchie, H.; Roser, M. Greenhouse Gas Emissions. 2020. Available online: https://ourworldindata.org/greenhouse-gas-emissions (accessed on 21 November 2020).
69. De Sario, M.; Katsouyanni, K.; Michelozzi, P. Climate change, extreme weather events, air pollution and respiratory health in Europe. *Eur. Respir. J.* **2013**, *42*, 826–843. [CrossRef] [PubMed]
70. Schröter, D.; Cramer, W.; Leemans, R.; Prentice, I.C.; Araújo, M.B.; Arnell, N.W.; Bondeau, A.; Bugmann, H.; Carter, T.R.; Gracia, C.A.; et al. *Global Change Vulnerability Assessments: Definitions, Challenges, and Opportunities*; The Oxford Handbook of Climate Change and Society; Oxford University Press: Oxford, UK, 2012.
71. CFI; SWO. Analysis, Analyzing a Company's Strengths, Weakness, Opportunities and Threats. Available online: https://corporatefinanceinstitute.com/resources/knowledge/strategy/swot-analysis/ (accessed on 9 August 2021).
72. De Giovanetti, L.; Volsteedt, J. Vertical Shaft Brick Kiln (VSBK) An effective South-South Technology Transfer for climate change mitigation in the Clay Brick sector. In Proceedings of the 16th International Union of Air Pollution Prevention Associations (IUAPPA) World Clean Air Congress, Cape Town, South Africa, 29 September–4 October 2013; pp. 1–5.
73. Erbe, S.O. Technical, Economical and Organisational Analysis of Informal Brick Production in Tercera Chica, Slp, Mexico. Master's Thesis, Cologne University of Applied Sciences, Cologne, Germany, 2011.