The Eastern Mediterranean charcoal industry: air pollution prevention by implementation of a new ecological retort system

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Key Points:

- The smoke released from the traditional process is being captured and condensed to wood vinegar.
- Improved charcoal production efficiency in the new system obsoletes the old polluting earth kilns
- Added heat to the process is just about 10% of the energy released from it.

Abstract

Earth kilns are still used for charcoal production in the Eastern Mediterranean and worldwide. Until 2016, around 1,600 tons of charcoal were produced in Israel and the Palestinian territories in about 400 traditional earth kilns that were operated in about the same manner for the last 400 years. The intense air pollution caused by this indigenous practice resulted in higher mortality rates among the workers and the population living close to the charcoal production sites. The air pollution was found to migrate beyond 50 km, causing cross-boundary pollution in Jordan. Since the charcoal production industry process surplus wood into solid fuel, which is used for heating and cooking, it was imperative to shift this industry to a new type of non-polluting charcoal production system. To upgrade this industry to 21st century standards development and implementation of a new ecological retort system (ERS), became possible through a combined effort by Israeli researchers and Palestinian manufacturers. Comparing the ERS to the old earth kilns suggests that the wood-to-charcoal transformation efficiency is about 10% higher in the ERS and the process duration is half a day vs. about three weeks in a traditional kiln. Generally, ERS is about two orders of magnitude more productive than the traditional earth kilns. The ERS combines a simple operational scheme and higher charcoal yield than a traditional kiln, leading to increase in the revenue to the charcoal makers, also through byproducts bearing economic value such as electric energy and wood vinegar.

Plain Language Summary

Charcoal production is still considered a polluting industry with a certain impact on global climate change. This traditional practice along the Eastern Mediterranean Sea shoreline exists since the iron age and was industrialized during the Ottoman Empire period, for fueling the Hijaz train engines. The charcoal production continued long after the Hijaz trainline ceased and gradually increased in magnitude, becoming a major environmental and health issue in the last couple decades. In parallel to the regulatory actions aimed at stopping the air pollution a development of new type of ecological charcoal production system involved cooperation between Palestinian charcoal manufacturers and Israeli researchers. This combined effort has led to the termination of the air pollution through implementation of the new system and the transformation of the land previously used for charcoal production into farming.

1. Introduction

Cooking and heating by wood, agricultural waste, dung, and coal is the cause of about 25% of black carbon emissions. On an annual average, the largest amount of charcoal production in the world is produced in Africa (around 64 percent in 2018) [Food and Agricultural Organization, 2020], followed by Asia and the Americas (mostly Latin America) [Food and Agricultural Organization (FAO), 2019]. According to a current assessment, 250 million people are using charcoal for domestic energy production at least once a week, mainly in Africa, some parts of Asia, and Brazil [Ezzati, 2003].

The top exporter of charcoal is Indonesia (309M$) and the top importer is Germany (127M$) [OEC, 2020], Brazil is considered the world's largest charcoal producer [Mugo and Ong, 2006; Anater et al., 2018; Food and Agricultural Organization, 2019], but is consuming all its production for internal use, mostly for the steel industry and the rest in households for cooking and especially barbecue [Anater et al., 2018]. Extensive charcoal industries also exists in Africa, Latin America, Asia and Europe [Tomaselli, 2007; Namaalwa et al., 2009].

In the carbonization process, about half of the wood's calorific value is lost [Laxton, 1844], nonetheless charcoal is the preferred fuel form over wood for several reasons: charcoal weighs less than wood and occupies less space since it is more easy to break into small pieces, and therefore is more convenient for transport and storage. Unlike charcoal, wood stored in improper conditions may be damaged by insects and fungi, thus reducing its energetic value. In addition, charcoal is a more concentrated fuel than wood, so burning it emits about 87% less smoke and toxic gases than wood [Francis Nturanabo, Gaston R. Byamugisha, 2011].

Charcoal production can be performed as a controlled industrial process, as for the iron industry in the United States [Baker, 1985] and for the metal processing and chemical industry in Southern Vietnam [Bhattarai, 1998]. Local traditional kilns as in Brazil, Senegal and Kenya [Kato et al., 2005; United Nations, 2006], and also the Eastern Mediterranean Sea Coast are also controlled to some extent. Charcoal production in the Eastern Mediterranean is a source of income for local communities since the iron age extending from Egypt at the south and up to Syria in the north and also to Jordan in the east [Bienkowski and van der Steen, 2001]. This indigenous tribal practice was industrialized during the ottoman period for fueling the Hijaz train line, which picked during world war one [Mitchell, 2009]. Since the shift from steam to diesel locomotives during the 20th century, charcoal demand was diverted to cooking and heating purposes, with increasing demand that collided with 21st century environmental standards [Ankona et al., 2021].

Traditional kilns have many varieties, but the charcoal production principle is the same, having dry weight basis efficiency that ranges from 10% to 22%. Among the traditional charcoal production methods, two techniques are the most common in developing countries: earth mound (above ground) and earth pit (underground) kilns [UNDPE, 2013]. The traditional kilns are operated by people of low working class, including children of both genders and in all traditional kilns, the charcoal production is accompanied by smoke and odor [United Nations, 2006].

Air pollution, deforestation, and land degradation have motivated several studies in an attempt to streamline a cleaner and more efficient charcoal production process and adapt it to a simple indigenous practice [United Nations, 2006; Adam, 2009]. Such studies led to the development of the Casamance kiln in Sweden, where the main improvements over the earth kiln are a flue circulation system and external chimney installation. Experiments carried out with this system in Senegal have shown that the chimney does improve the gas circulation, shorten the process, and increase the charcoal yield. Casamance kilns were extensively used for charcoal in the iron industry, but they were later replaced by brick kiln systems, such as the Brazilian beehive kilns, the Argentine half-orange kiln, the European Schwartz kiln, and also the Missouri kiln in the U.S.A. Favorable systems should be built from low-cost materials such as clay and sand, and produce high quality charcoal at higher yield than earth kilns [FAO forestry, 1987].

Retort technology-based kilns accelerates the charcoal production process by efficient isolation and gas emission recycling. The retort kilns are more efficient, having over 30% efficiency vs. ~20% in the traditional kilns. Since the smoke produced in the retort kilns is partially burned in the carbonization process, the air pollution is reduced by about 70%. The improved production process is shortened to 24-30 hrs. compared to 3–5 weeks in the traditional technology [Gomaa and Fathi, 2000]. The retort kilns are heated externally, and the gases emitted from the wood thermal decomposition are circulated to the pyrolysis chamber as fuel. In the upgraded process the kiln temperature can be controlled by regulating the fuel supply to the external heater and the biomass fuel to the pyrolysis chamber; as most of the tar and gas components are burned, with the heat used for the carbonization process [GIZ, 2014].

There are two charcoal retort types, the pastoral type has a chimney and wood processing to charcoal is accompanied by some air pollution emissions and the more industrial type is without a chimney and does not emit gases but instead provides a dark liquid concentrated by-product called wood vinegar. The charcoal production system development, described in this paper have evolved from an initial pastoral retort type to a pastoral modification to the industrial retort type [Sweet Ankona et al., 2018].

1.1. The charcoal production industry in Israel and the Palestinian Authority

The local charcoal production industry is typical to Muslim villages as a traditional practice, especially in northern Samaria and to Druze villages in the Galilee, in an industrial form. This industry has four main operating entities: the orchard owner (raw material source), the lumberjack (raw material marketer), the timber transport contractor (raw material distributor), and the charcoal producer. Sometimes the lumberjack, transport contractor, and charcoal owner are all the same entity. In addition, there are also paid "mediators" who link the orchard owners with the lumberjacks.

While in Israel charcoal demand is not daily but focused on family events, holidays, and festivals (Ramadan, Nabi Shuaib, Passover, Sukkot, Independence Day, etc.), in the Palestinian Authority the demand is daily for cooking and heating. The woods commonly used for charcoal making are citrus and avocado woods [Sweet Ankona, et al., 2018].

The traditional earth kilns that operated in northern Samaria were designed so that large wood pieces are placed in the kiln center in a way that allows air to flow at the bottom of the woodpile. All wood parts are then covered with twigs and soil, and the air openings are located at the bottom of the kiln [Oduor et al., 2006]. The earth kiln construction is simple and is based on skilled wood piece arrangement and air conduit alignment. The kiln construction cost is low, but the charcoal producing process is long and cannot be upscaled to an industrial level. The traditional charcoal process causes air pollution emissions at levels exceeding any environmental regulations, especially in the last three days of the combustion process [Marais and Wiedinmyer, 2016].

1.2. Charcoal production as a regional nuisance

Before its termination in 2016, traditional charcoal production was held in the area A (exclusively administered by the Palestinian National Authority) and area B (administered by both the Palestinian Authority and Israel), after being removed from area C (administered by Israel) in 2012 [Sweet Ankona, et al., 2018]. This industry was the main source of barbecue charcoal for the region and the livelihoods of hundreds of families, through the operation of about 400 kilns. Most of the charcoal wood raw material originated from Israeli farmers who uproot avocado orchards and old orchards. The kilns were located at the village outskirts from which thick smoke spread throughout the area causing severe air pollution and harming both the Israeli and Palestinian residents of the area [Ozen, 2010].

The air quality tests conducted by the Israeli Ministry of Environmental Protection in Israel, south of the production area, consistently showed high levels of fine breathable particles smaller than 2.5 microns and high concentrations of carcinogens, both exceeding the levels demanded in the clean air health regulations [Cordova, 2012]. Citizens' complaints about the charcoal kiln smoke odors indicated that the smoke reached the city of Hadera, approximately 25 km away (aerial line). Repeated reports of smoke nuisances in Israeli localities, as Harish, Karkur and Hadera motivated delay in the sale of houses in the developing locality of Harish, rising the need for solution to the problem [Ministry of Agriculture and Rural Development, 2016]. The situation severity was reflected in a lower-than-average life expectancy in Palestinian localities whose residents made a living from charcoal production [PCBS, 2015]. To reduce the nuisance, raw material transfer to the area was prevented by legislative actions, accompanied by intensive enforcement operations that were carried out by the Civil Administration in 2011-2012. All kilns in the areas of Israeli civilian control (C area) were abandoned, and the charcoal kiln activity migrated to the Zibda-Ya'bad route in area B (Figure 1).

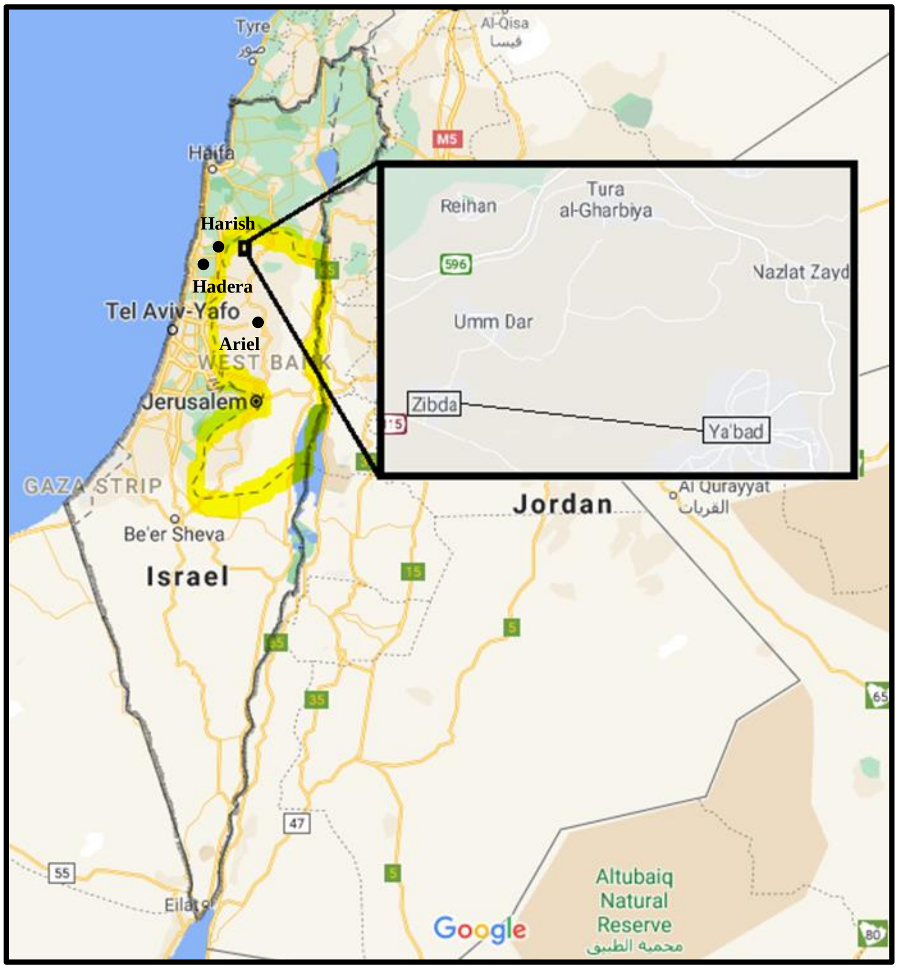


Figure 1. Location map of pilot sites, with insert of the Zibda-Ya'bad route.

Once these efforts failed and the pollution continued, it was decided to develop an ecological retort system (ERS) for environmentally friendly charcoal production, characterized by low intensity operation, being almost a natural process adapted to the needs of the indigenous community and not fundamentally different from the operation of traditional kilns.

(a)

2 Materials and Methods

2.1 The ERS description and application

Three new ERS prototypes were built. Initially, two prototypes were built at Ariel University (Figures 2a & 2b) and one at the Zibda-Ya'bad route (Figure 2c). The first prototype was constructed on a reduced scale (for 100-200 kg of wood) with an identical operation scheme as the traditional wood-heated systems. The small size of the system was necessary to allow faster control over the process and to perform more runs with less wood for each operation. The system size also allowed some retrofitting which helped to reduce the smoke emission by about 90% relative to the traditional kiln operation. Still, the air pollution rates were found to be too high, and the second full scale (1000-2000 kg of wood) prototype was designed with gas condensing that reduced pollution emissions to imperceptible levels. The third prototype was built and operated at the Ya'bad site with the same chamber volume size as the second prototype.

Figure 2. The prototypes that were built at Ariel University: (a) Prototype 1 (capacity 100-200 kg of wood) and (b) Prototype 2 (capacity 1000-2000 kg of wood). The third ERS prototype (c) was built and operated at the Ya'bad site in the Jenin area. The system's structure consists of: (1) the body of the kiln; (2) the hoist for lifting and lowering the lid; (3) the condenser system for gas absorption.

The second prototype (Figure 2b) is the scale up of the initial small prototype that was aimed for testing and developing an operative pyrolysis method; yielding maximal charcoal amount in minimal operation cycle time. The third prototype (Figure 2c) operates at the Ya'bad site and replaces the traditional kilns of northern Samaria, is automated with a computerized control system. In the third prototype development stage an optimized operation program with designated operation stage duration and pyrolysis temperature, was assigned for each wood type fed to the system. All prototypes included two typical key processes: 1. a water circulation system, which supplies water to a spiral heat exchanger around the kiln, cooling it and conducting steam to generate electricity (Figure 3) and 2. a retort apparatus that recycle and condense the harmful emissions during the charcoal production process (Figure 4). The ERS skeleton is made of steel and a heat resistant concrete cast (in the full-scale systems), with a lid that is raised or lowered using a hoist pulley. The ERS consists of two chambers: the combustion chamber built below the ground and the pyrolysis chamber situated at the ground level.

Figure 3. Cooling pipe systems (a) heat converter illustration; (b) Ariel University pilot with wood arrangement in the pyrolysis chamber and (c) the steam turbine operation at the Ariel pilot.

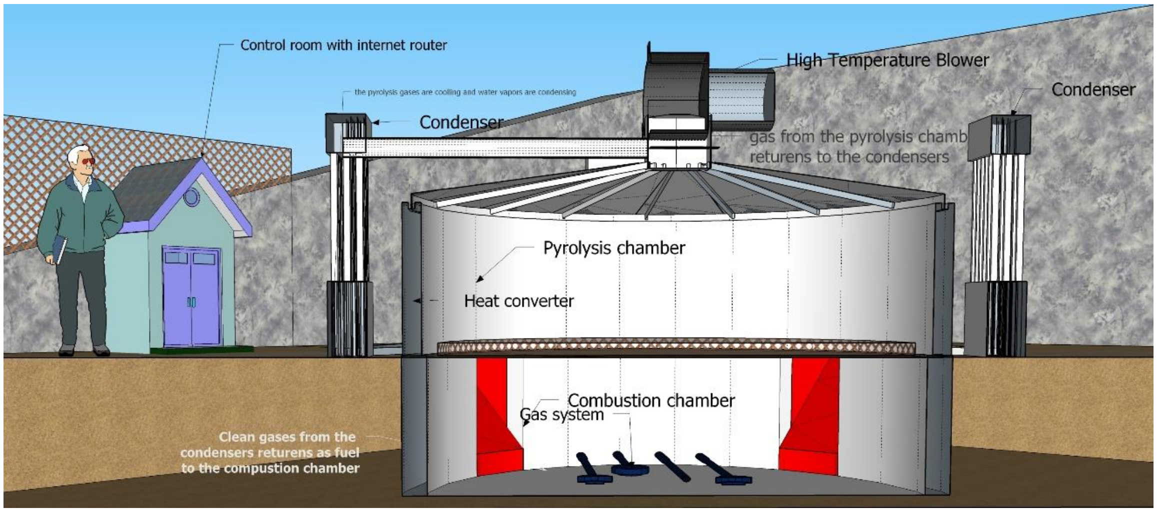


Figure 4. Vertical cross section of the ERS.

2.1.1. The combustion chamber

The combustion chamber is positioned underground to reduce the operating area height and to allow the carbon dioxide to drain from the pyrolysis chamber during the spontaneous heating stage. To reduce emissions, the system can be heated with cooking gas [Peters et al., 2015]. The access to the combustion chamber is arranged through doors that form part of the pyrolysis chamber base and the combustion chamber roof (Figure 4). It is possible to control the oxygen amount in the process by the air vents and the blowers. The system heating is performed using a hybrid system composed of cooking gas and recycled flammable gases.

2.1.2. The pyrolysis chamber

The upper floor of the ERS system is the pyrolysis chamber, in which the wood is converted into charcoal. To maintain the desired operating temperature with a nominal energy input the chamber is insulated. The pyrolysis chamber base is a heat dispersion surface that is made of an iron mesh on which the raw woods are placed, and above it there is a convex-shaped metal tin-plate installed that serves as a radiation reflector. The system upload and offload are carried out by the roof hoist driven by an electric lifting system and manual lateral movement.

2.1.3. Water circulation system

The water circulation system functions as a heat exchanger in the space between the pyrolysis chamber and the wall of the installation (Figure 3). Apart from the charcoal production, the heat generated in the ERS may be used for energy production by a turbine system or a heat exchanger. For surplus heat control, a water circulation system is activated by thermodynamic propulsion of the water in the kiln. For receiving continuous steam that allows generation of electricity throughout the charcoal production process, the water system can be operated by regulating the amount of water supplied to the heat exchanger. In the cooling stage, running the water circulation at full capacity shortens the stage duration without increasing emissions or damaging the quality of the charcoal, modifying the system so steam that will be released at the pyrolysis peak temperature, can enable the charcoal is activation.

2.1.4. Gas recycling and filtrating system

The carbonization process is accelerated by a cascading condenser system that recycles the emitted gases and prevents air pollution. While at the Ya'bad site there are six condensers, the initial design in the Ariel full-scale pilot had four condensers. The two additional condensers at Ya'bad were needed owing to the industrial manner of operation. The higher than atmospheric pressure pyrolysis gases are led by blowers to the initial condenser pair, and, while compressed down through the condensers, they are cooled and condensed on a polypropylene mesh assembly. The gas condensate from the initial condenser stage drains into a collection tank as an aqueous solution known as wood vinegar. The gas that did not condense continues to the second condenser stage, where the same process takes place as in the initial condenser stage. The process repeats once more in the tertiary condenser by means of fine filtration through a biotech fabric made of polyethylene terephthalate (PET) hollow fibers and capture of residual condensation products if any. The tertiary stage is intended to purify the gaseous phase into synthesis gas for use in subsequent operations and the emission of filtered carbon dioxide, which has an economic value (Figure 5).

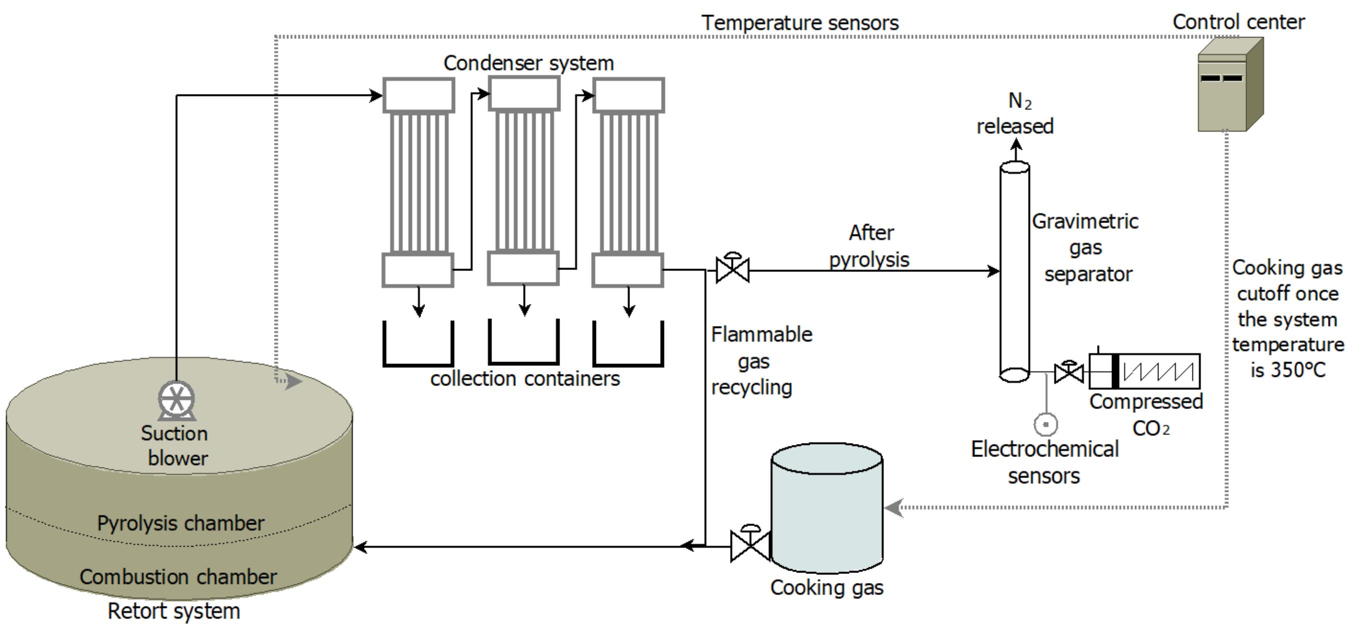


Figure 5. The ERS gases recycling system process illustration.

2.2. The ERS operation

Woods of the same type and moisture are cut to a length of about a meter, split into similar size prisms, and left to dry in the sun. When its moisture is lower than 15%, the prisms are placed next to each other on the iron mesh inside the pyrolysis chamber (Figure 3). In the case of operation without external fueling, firewood used for heating includes types of wood not appropriate for coal production (e.g., twigs, pine, or landscaping waste) that are organized in the combustion chamber at intervals of 20 cm from each other, to allow availability of oxygen for the initial combustion. Once fired, the feed doors are closed, and the vents are gradually closed and reopened if additional oxygen supply is required for the combustion chamber.

Once the system temperature reaches 300^{o}C the system is totally isolated from atmospheric oxygen and once reaches 400^{o}C also the gas circulation system is shutdown. Once temperature reaches 450 ^{o}C the water circulation is opened for fast cooling of the system to ambient temperature. The charcoal offload takes place when the temperature of the pyrolysis chamber drops to ambient temperature and it should be carried out by personnel wearing face breathing masks and gloves, since charcoal is weighed and collected into suitable bags using appropriate metal dust dustpans.

2.3. Continuous air monitoring system

2.3.1. The control system

In the charcoal producing process, the ERS is equipped with a control system the function of which is to manage the operation (Figure 6). The main variables used for the process control are the pyrolysis chamber temperature (Figures 7 & 8) and a 3Gtrack radiation sensor designed to monitor the fire and give an index for operating the blowers, valves, and cooling system. The temperature measurement (3Gtrack, T_A2_HT, 0–850°C) was performed continuously at a frequency of one minute using the sensors with a pt100 input signal mounted on three levels in the ERS system wall: at the bottom of the combustion chamber, on the boundary between the combustion chamber and carbonization chamber, and on the roof of the ERS system. The data was stored in a 3Gtrack, GS828-H2 transmitter data repository from where it was sent to a data storage server.

2.3.2. The Meteorological station

As part of the control system, a meteorological station was installed whose function was to enable the examination of emissions from the system under different synoptic conditions and was also applied to the Ya'bad site through nearby existing meteorological stations.

The meteorological station (Figure 6) includes a temperature and humidity meter (TH_V3), as well as wind speed (3Gtrack, WS100) and direction (3Gtrack, WD100) sensors and a 3Gtrack CO_2 content sensor.

Figure 6. The monitoring system components: (a) high temperature sensors; (b) humidity and air temperature sensor; (c) CO_2 concentration sensor; and (d) data collecting device.

2.3.3. Flue gas analysis

An electrochemical sensor based continuous gas emission monitoring system was installed near the Ya'bad site ERS. Gas entering the sensor causes an electrochemical reaction changing the potential depending on the gas concentration, which may be determined according to a calibration curve provided by the sensor manufacturer. This conversion is performed by a programmed controller using a designed code. Several sensors are installed, the gases concentration range detected by the MQ2 gas sensor module sensor system is 30-10,000 ppm, for each of the gases: liquefied petroleum gas (LPG), alcohol, propane, hydrogen, methane carbon monoxide and smoke; by MQ131 semiconductor sensor the range is10 ppb to 1 ppm ozone, chlorine and nitrogen dioxide; 10-300 ppm ammonia, 10-1000 ppm benzene, 10-300 alcohol by MQ135 gas sensor module; and 1-200 ppm hydrogen sulfide gas by MQ136 semiconductor sensor. The system is connected to the Internet and uploads the information in real-time to a website (https://thingspeak.com/channels/public?username=asherun) developed specifically for the Ya'bad system. The system's detection limit is correlated with the Ministry of Environmental Protection standards, and it is built in a way that it can be placed at any site where air quality needs to be monitored. The sensors validation in the laboratory and at the Ariel University site was done with Agilent Cary 630 FTIR system in flow-through gas analysis assembly.

2.4. Development of heat-resistant bricks

The purpose of this section was to test and select a lower cost of materials that can replace natural aggregates of the concrete mixture to build the kiln. The resistance of the concrete mixtures to heat was tested and characterized by compressive strength of the bricks. The heat resistance test of the concrete bricks was performed using a carbolite STF16/160 laboratory tube furnace (MRC, London, UK). All the concrete components were mixed in an electric portable concrete mixer for 10 minutes. The compressive strength was tested according to the Israeli standard (SI 26 part 4.1) by testing concrete cubes having dimensions of 10×10×10 cm. After samples solidification, bricks from each batch were gradually (10ºC/min) heated in the furnace to a temperature of 800℃ and a corresponding brick was kept outside the furnace as a control. Seven days later, the heated bricks and the reference bricks were pressed using a laboratory press with 5×5 cm mold grid device, to examine a change in their compressive strength after the heating. the brick's heat durability is recorded at percentages which represent the compressive strength of the bricks after heating in the furnace in relation to the compressive strength of the bricks before heating in the furnace which was measured in MPa units. Initially, local soil samples were collected from different sites to test them as local aggregates to build the kiln. Two soil types were collected from Na'aran at the Jordan Valley (Vertosol and iron Vertosol soils). Rendzina was sampled from the University site where the initial research was conducted, and Terra Rossa was collected at the Ya'bad area in northern Samaria.

Subsequently, we tested the heat-resistance of each of the local soils collected according to the concrete composition that were found to be suitable, determined by the effect of the concrete components (cement, fly ash and local soil) on the brick's heat resistance and according to the working comfort of the concrete formation.

2.5. Field Emission Scanning Electron Microscope (FE-SEM)

A sample of the charcoal produced from citrus woods at 550°C by the third ERS prototype was collected and kept in the dissector until the analysis to prevent moisture accumulation. The morphology of the charcoal produced and the mineral composition on its surface were evaluated by the Field Emission Scanning Electron Microscope (FE-SEM) (Tescan MAIA3), with the Aztec EDS (Energy Dispersive X-Ray Spectroscopy) Oxford microanalysis system. The analysis was performed by operating at 8.0 kV using a small amount of charcoal sample powder adhered onto a carbon stub using double-sided carbon tape. The adjustment of the relative weights of the elements in the area tested as obtained in the EDS microanalysis and the identity of the mineral was done using the dedicated Mineralogy Database website (http://webmineral.com).

3 Results, or a descriptive heading about the results

Operation of the ERS system included the following stages: drying and initial decomposition by aerobic combustion, exothermic decomposition, completion of carbonization, and cooling (Figure 8). The averaged charcoal yield was 32.0%±1.5% on an oven-dry basis. The formulated operating method enabled reproducibility operation provided by consistent yield.

3.1. Heat resistance test of the developed concrete bricks

The effect of each concrete brick component (cement, local soil, and fly ash) on the brick compressive strength was tested. Table 1 presents the compressive strength of the concrete cubes which were tested, before and after the heating process. As can be seen, significant reduction in compressive strength was obtained by using the local soil or by preparing the concrete with only pure cement. However, when using fly ash as a partial replacement for cement, strength reduction was insignificant. It was found that with respect to Portland cement brick strength, soil addition caused reduction in heat resistance of the bricks by about 10.2%, while fly ash addition improved brick heat resistance by about 152%. The effect of the different local soil types (Vertosol, iron Vertosol, Rendzina and Terra Rossa) on the heat resistance of the bricks was tested. Table 2 presents the compressive strength resistance for mix design of different concrete mixtures having various soil types. Besides Rendzina the addition of soil to the concrete mixture reduced in ~50% the concrete compressive strength. Rendzina soil maintained a compressive strength of about 91% which is about the same as that of the pre-heated reference bricks.

Table 1. The bricks relative strength

Component	***a***	***b***	***c***	***d***
Portland Cement (CEM II42.5N AM), wt. %	100	50	50	20
Local Rendzina soil (Ariel University), wt. %		50		40
Fly ash, wt. %			50	40
Resistance to compressive strength, % from compression strength of reference bricks.	59	53	90	91

*100% - Compression strength of reference bricks - bricks that have not been placed in the furnace.

Table 2. Examination of the effect of different local soil on brick strength.

Component	***Brick without soil***	***Rendzina, Ariel University***	***Terra Rossa, Ya'bad***	***Iron Vertisol, Jordan Valley***	***Vertisol, Jordan Valley***
Portland Cement (CEM II42.5N AM), wt. %	50	20	20	20	20
Local soil (Ariel University), wt. %		40	40	40	40
Fly ash, wt. %	50	40	40	40	40
Resistance to compressive strength, % from compression strength of reference bricks.	90	91	52	53	55

*100% - Compression strength of reference bricks - bricks that have not been placed in the furnace.

Apparently, unlike the other clay-rich soils examined, Rendzina that is a calcareous clayey soil rich in limestone [Jacquin et al., 1992], as such, in the heating a calcination thermo-chemical process takes place [Mikulčić et al., 2012], in which limestone is converted by thermal decomposition into quicklime (CaO) that contributes to better thermal performance and heat resistance properties is obtained [Jacquin et al., 1992].

3.2. Temperature profile of the ERS system

During the drying stage, the temperature reached a maximum of about 300°C. This stage was relatively fast - between 40 minutes and 1.5 h, depending on the initial humidity of the woods, ranging at 6-15%. In the first operations, when the system heating was carried out using firewood, the combustion chamber door was partially open and according to the fire condition check in the combustion chamber, when operating without external heating, heating woods were added while weighing and listing the added woods. It was found that the weight of the firewood required to operate the system, without the need to add additional firewood during the operation, is about 10% of the charcoal wood weight. When the temperature reached 200°C, the combustion was established. On reaching 270°C, it was possible to close the doors of the air supply openings to the combustion chamber, and when the temperature started to drop, the air vents were again opened a little bit. The system heating in the combustion chamber can be carried out by wood or hydrocarbon fuel burning and in the latest prototype - by electricity.

At the stage of exothermic decomposition, there was a controlled temperature increase up to 350°C. This stage was short and lasted between 60-90 minutes. The end of the carbonization process was accompanied by an additional temperature increase that reaches a temperature of between 450 to 500°C. The carbonization completion step lasted between 30 to 60 minutes. At the end of the carbonization process, the water circulation system caused a decrease in the system temperature. The cooling process lasted about 5 hours, during which the temperature gradually dropped below 100°C. The changes described in the temperature profile during the entire time of the kiln operation are shown in Figure 7. The charcoal collection was carried out when the temperature dropped to the ambient temperature.

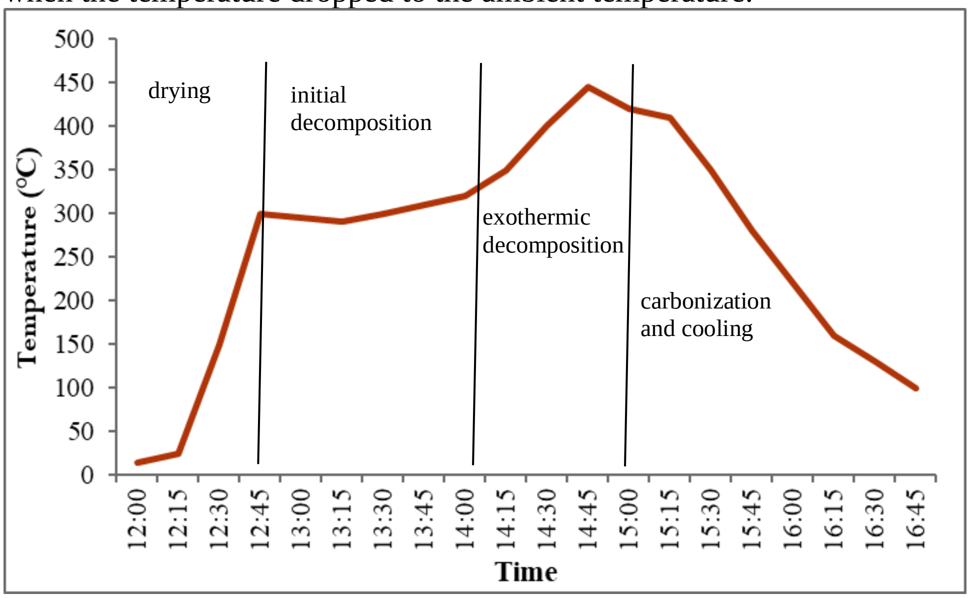


Figure 7. Curve of carbonization chamber temperature measured by pt100 temperature sensor located on the ERS upper level versus time during ERS activation.

In the first operations of the second prototype, owing to technical issues of insolation and leaks from the gas recycling system, the thermal decomposition took place at a low carbonization temperature between 350-400°C (Figure 8). These operations gave a higher yield of charcoal but this charcoal was considered of a poorer quality since the it still contained considerable amounts of the tar residue from incomplete decomposition of the original raw wood [FAO forestry, 1987]. In order to ensure heat consistency, the following operation were done with a gas heating system (Figure 4).

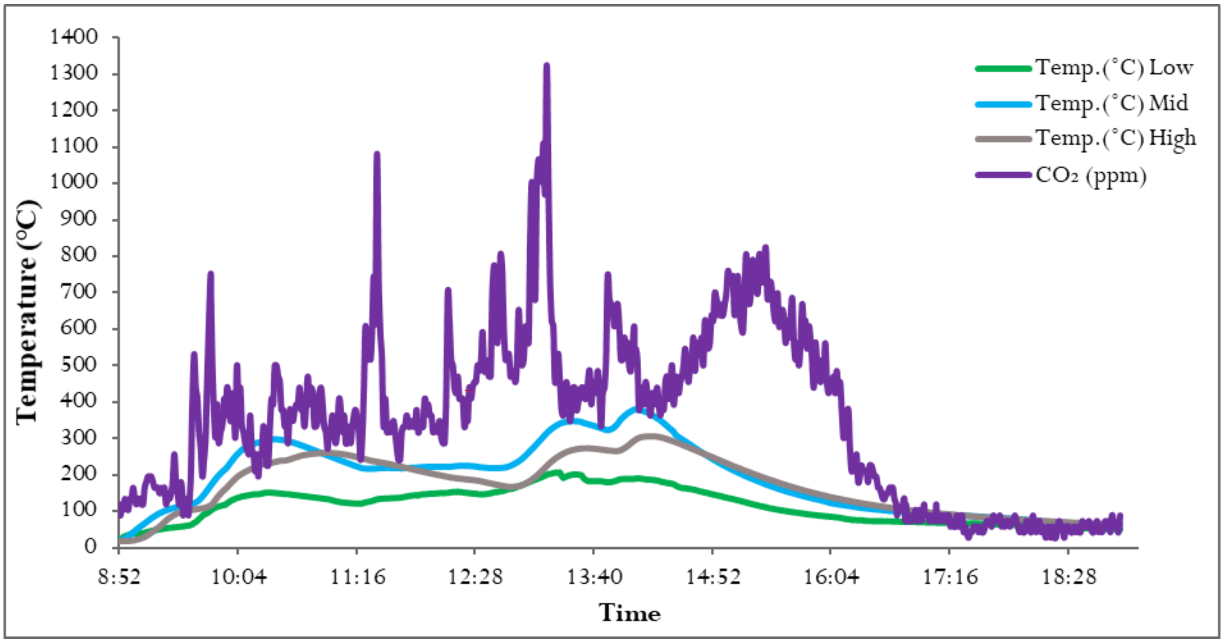


Figure 8. Carbon dioxide curve in the carbonization chamber wall (purple), and temperatures curves on the three levels in the ERS system wall: at the bottom of the combustion chamber (green), on the boundary between the combustion chamber and the carbonization chamber (azure), and on the roof of the ERS system (gray).

3.2. Continuous air pollution monitoring system

The continuous monitoring system worked well, regardless of wind direction, except for the carbon dioxide sensor when the wind direction was east, which can be seen as peaks in Figure 8. The other changing parameters operated satisfactorily and allowed real-time control of the carbonation process. The gas circulation system of the first and second prototypes enabled the kiln activity to cause zero disturbance on the Ariel University campus regardless of wind direction. While the gas sensor system proved that the emissions were minor and below the detection range of the sensors in both sites, the laboratory test with the FTIR system suggests that without the condensers system, the pyrolysis process emits in addition to carbon dioxide also NOx and volatile hydrocarbon compounds (Figure 9). The implementation of larger and stronger suction capacity in the third system completely prevented the air pollution. The adjustment was carried out in the construction of the system at the Ya'bad site and by adding two condensers with the same volume as the existing ones. This enabled an optimal operating method and constitutes a good synergy between the system yield, the operating time (two operations can be performed per day), and air pollution elimination.

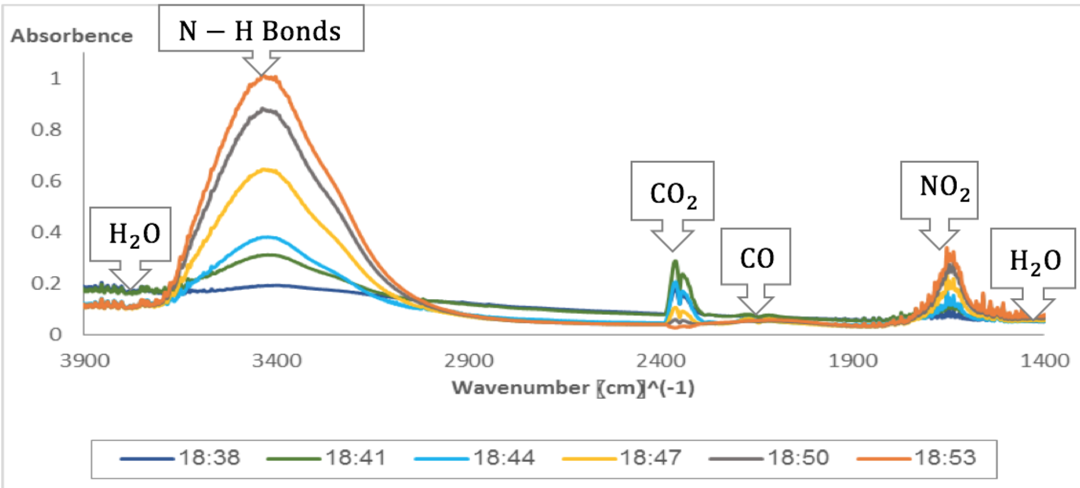
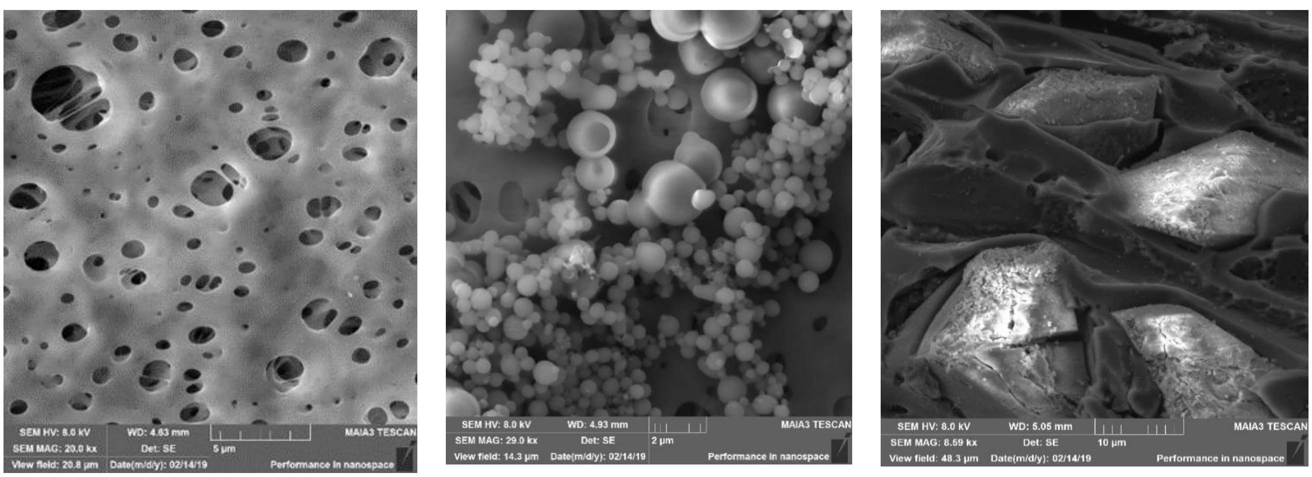


Figure 9. Continuous measurements of flue gas in a FTIR system

3.3. Charcoal morphology

Charcoal morphology was examined by SEM showing charcoal pores (hollow circles) scattered on the surface giving the charcoal its adsorption capacity (Figure 10a). Charcoal surface was partially covered by spherical particles (Figure 10b), identified as tar balls analogous to those obtained after biomass combustion reported in the literature [Li et al., 2003; Pósfai et al., 2004; Gorkowski et al., 2013; Makonese et al., 2019]. Inclusions seen in Figure 10c were identified as calcite crystals located in the charcoal pores. Wood, and especially its bark, is a rich source of calcium [Lambert, 1981] which is converted to CaO during the wood pyrolysis process and is captured in the formed charcoal pores. Formation of a calcite mineral ($CaCO_3$, Figure 10c) is by reaction of the formed CaO with CO_2 [Tintner et al., 2018].



a b c

Figure 10. SEM images of charcoal from ERS system. a. charcoal surface, b. tar balls and c. mineral calcite trapped in the charcoal pores.

3.4. Valuable by-products

The ERS was aimed to replace the polluting kilns, which do not meet current environmental standards, without compromising the socio-economic stability of the charcoal producer's community. To assist in the implementation of the new system additional economic products beside charcoal were developed as auxiliary income source to the charcoal manufacturers. Since the pyrolysis gases are not released in the ERS, upon cooling down they condense into wood vinegar, with a composition and properties depending on the source material and pyrolysis regime (time and temperature). This is a dark liquid with a strong smell having a variety of uses. The wood vinegar is mentioned in Jewish sources in Seder Moed - Tractate Shabbat (Chapter 2, Mishnah B) as a material for combustion. This substance is also mentioned in the Qur'an (Sura Ibrahim verse 50) as a substance for various uses: as a dye, a flavor for food, and especially a substance for the treatment of camels - treatment of friction and other wounds, as a lubricator of hooves, and is also found as an insect repellent [Yatagai et al., 2002; Kiarie-Makara et al., 2010].

In addition to the ancient practice of horse hoof lubrication, wood vinegar can be useful in ecological agriculture for plant disease treatment, pest control, accelerating crop growth, improving fruit quality, and as a herbicide [Yoshimoto, 1994]. This substance is also used in the cosmetics industry: studies have shown that wood vinegar exhibits antioxidant and antibacterial activity [Yang et al., 2016]. In the ERS, wood vinegar is formed in the amount of about 30% of wood mass introduced into the system. Currently, the antibiotic properties of various chemical components of the collected wood vinegar are being tested in our laboratory.

Flammable gas is another product of economic value obtained in the ERS process. This flammable mixture includes mainly hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and volatile organic gases such as methane (CH_4) [Berrueco et al., 2005] that are considered problematic in their emission. In all the prototypes, this flammable gas was recycled to regulate the operating temperature. In the Ya'bad prototype, the flammable gas replaced the cooking gas once the operating temperature reached about 300^{o}C.

While it was intended to implement the ERS in parallel to law enforcement measures, the increase in public pressure and the expansion of the charcoal manufacturing industry led to the closure of all the kilns operating in area A, and especially in area B during 2016, in parallel to the construction of the ERS systems. These changes motivated the local population to convert the areas vacated from charcoal production to tobacco growing, which was an important agricultural product in the area (Figure 11).

Figure 11. Tobacco cultivation in the areas vacated due to the cessation of charcoal production.

5 Conclusions

The ERS produces charcoal without emitting air pollution, and with higher efficiency than traditional charcoal. The cylindrical kiln structure ensures uniform dissipation of heat and of the oxygen with recycled gas mixture that is fed to the combustion chamber. This allow controlling the accelerated retort system, which almost completely prevents pollutant emissions. Another advantage of the system is a shortening of the operating time of the system cycle to 2-4 hours of operation and 5 hours of cooling, compared to at least 3 weeks in traditional technology.

Examination of the advanced prototype at the Ya'bad site shows that it is characterized by high efficiency as 32.0±1.5% compared to up to about 22% in traditional kilns, which is like the charcoal yield obtained from known retort systems (Basu & Blodgett 2013; Oliveira et al. 2014; Sparrevik et al. 2015).

The ERS prototype in Ya'bad is the only industrial system that has received environmental standard approval from the local authorities. Since the system was handed over to the landowners, no air pollution hazards have been reported. The ERS system operation is carried out by local people and so far without complaints of neighboring communities, or abnormal readings at the site's air quality monitoring system, although in the summer of 2019 one anomalous NOx and Cl_2 concentrations were recorded in the online monitoring system, apparently without an environmental impact.

The device structure can be metal plated or casted from local material bricks that can withstand the kiln heat, but it requires proper maintenance. It was found that the plaster should be regularly inspected, and cracks that appear should be repaired after each operation. In case the plating is metallic, once a month it should be checked for corrosion of the metal and treated accordingly.

Despite some opposition to traditional kiln termination, the charcoal industry workers transitioned to healthier industries such as agriculture (growing tobacco, Figure 12), trade, and other unskilled day jobs. The high efficiency of the new retort can ensure more efficient and cleaner operation of this indigenous local industry and small systems as the first prototype can be practical for farmers as demonstrated by farmers in Egypt to dispose of agricultural pruning without creating pollution, and for the secondary production of charcoal for personal use [Gomaa and Fathi, 2000].

During the transition from the old system to the ERS, a significant part of the production was diverted to industrialized systems in Egypt. The increase in Egyptian charcoal demand aggravated air pollution at the Egyptian production site until the Egyptian systems were equipped with the same air pollution prevention condenser systems that were developed in the framework of this project.

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References

Adam, J. C. (2009), Improved and more environmentally friendly charcoal production system using a low-cost retort-kiln (Eco-charcoal), *Renew. Energy*, *34*(8), 1923–1925, doi:10.1016/j.renene.2008.12.009.

Anater, M. J. D. N., J. F. Escobar, and S. T. Coelho (2018), Charcoal quality in the household consumption in Brazil, in *European Biomass Conference and Exhibition Proceedings*, vol. 2018, pp. 1202–1208.

Ankona, E., V. Multanen, M. Nisnevitch, M. Billig, and Y. Anker (2021), Investigation of pyrolysis kinetics and gaseous compounds emitted during charcoal production from woods commonly used in the Eastern Mediterranean, *Biofuels, Bioprod. Biorefining*, *2021*(1), 1–11, doi:10.1002/bbb.2188.

Baker, A. . (1985), Charcoal industry in the U . S . A ., in *Pretoria. Republic of South Africa. South African Council for Scientific and Industrial Research*, vol. 5, pp. 12–22. [online] Available from: https://www.fpl.fs.fed.us/documnts/pdf1985/baker85a.pdf

Berrueco, C., E. Esperanza, F. J. Mastral, J. Ceamanos, and P. Garcı (2005), Pyrolysis of waste tyres in an atmospheric static-bed batch reactor : Analysis of the gases obtained, *J. Anal. Appl. Pyrolysis*, *74*, 245–253, doi:10.1016/j.jaap.2004.10.007.

Bhattarai, T. N. (1998), Charcoal and its Socio-Economic Importance in Asia : Prospects for Promotion, *Pap. Present. Reg. Train. Charcoal Prod. which was held Pontianak, Indones.*, (February), 1–12.

Bienkowski, P., and E. van der Steen (2001), Tribes, Trade, and Towns: A New Framework for the Late Iron Age in Southern Jordan and the Negev, *Bull. Am. Sch. Orient. Res.*, *323*(323), 21–47, doi:10.2307/1357590.

Cordova, L. (2012), *Summary report of environmental inspections of kiln operations in Judea and Samaria*, Tel Aviv, Israel. [online] Available from: www.sviva.gov.il

Ezzati, M. (2003), How charcoal fires heat the world, *Environ. Sci. Technol.*, 160–161.

FAO forestry (1987), Simple Technologies for charcoal making, p. 41, FAO, Rome.

Food and Agricultural Organization (2019), Forestry Production and Trade, vol. 2019, Rome, Italy.

Food and Agricultural Organization (2020), Sustainable charcoal production for food security and forest landscape restoration I., *FAO*, (February), 2015–2020.

Food and Agricultural Organization (FAO) (2019), *Global forest products facts and figures 2018*, Rome, Italy.

Francis Nturanabo, Gaston R. Byamugisha, G. C. P. (2011), performance appraisal of the casamance kiln as a replacement to the traditional charcoal kilns in uganda., in *Second International Conference on Advances in Engineering and Technology*, pp. 530–536.

GIZ (2014), *Towards sustainable modern wood energy development*. [online] Available from: http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/giz2015-en-report-wood-energy.pdf

Gomaa, H., and M. Fathi (2000), A simple charcoal kiln for hardwoods or other dense biomass, *ICEHM2000*, 167–174. [online] Available from: http://www.virtualacademia.com/pdf/clea167_174.pdf

Gorkowski, K., A. C. Aiken, M. K. Dubey, and C. Mazzoleni (2013), freshly emitted wildfire carbonaceous particles, *Nat. Commun.*, 1–7, doi:10.1038/ncomms3122.

Jacquin, F., H. Cheloufi, and P. C. Vong (1992), Immobilization and mineralization kinetics of a nitrogen fertilizer in calcareous clayey soil (rendzina), *Sci. Total Environ.*, *117–118*, 271–278, doi:https://doi.org/10.1016/0048-9697(92)90094-9.

Kato, M., D. M. Demarini, A. B. Carvalho, M. A. V Rego, A. V Andrade, A. S. V Bonfim, and D. Loomis (2005), World at work: charcoal producing industries in northeastern Brazil., *Occup. Environ. Med.*, *62*(2), 128–32, doi:10.1136/oem.2004.015172.

Kiarie-Makara, M. W., H.-S. Yoon, and D.-K. Lee (2010), Repellent efficacy of wood vinegar against Culex pipiens pallens and Aedes togoi (Diptera: Culicidae) under laboratory and semi-field conditions, *Entomol. Res.*, *40*(2), 97–103, doi:10.1111/j.1748-5967.2010.00265.x.

Lambert, M. J. (1981), Inorganic Constituents in Wood and Bark of New South Wales Forest Tree Species, *For. Comm. N.S.W. Res. Note No. 45*, *45*, 45.

Laxton, W. (1844), Scientific and Railway Gazette, in *The Civil Engineer and Architect's Journal*, vol. 7, p. 444.

Li, J., M. Pósfai, P. V. Hobbs, and P. R. Buseck (2003), Individual aerosol particles from biomass burning in southern Africa: 2. Compositions and aging of inorganic particles, *J. Geophys. Res. Atmos.*, *108*(13), 1–12, doi:10.1029/2002jd002310.

Makonese, T., J. Meyer, and S. von Solms (2019), Characteristics of spherical organic particles emitted from fixed-bed residential coal combustion, *Atmosphere (Basel).*, *10*(8), 1–16, doi:10.3390/atmos10080441.

Marais, E. A., and C. Wiedinmyer (2016), Air Quality Impact of Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa), *Environ. Sci. Technol.*, *50*(19), 10739–10745, doi:10.1021/acs.est.6b02602.

Mikulčić, H., E. von Berg, M. Vujanović, P. Priesching, L. Perković, R. Tatschl, and N. Duić (2012), Numerical modelling of calcination reaction mechanism for cement production, *Chem. Eng. Sci.*, *69*(1), 607–615, doi:https://doi.org/10.1016/j.ces.2011.11.024.

Ministry of Agriculture and Rural Development (2016), *The report of the inter-ministerial team to reduce the problem of charcoal kilns*, Beit Dagan, Israel.

Mitchell, T. (2009), *Carbon democracy*.

Mugo, F., and C. Ong (2006), *Lessons from eastern Africa's unsustainable charcoal business*, Eastern Africa Regional Programme, Niairobi.

Namaalwa, J., O. Hofstad, and P. L. Sankhayan (2009), Achieving Sustainable Charcoal Supply from Woodlands to Urban Consumers in Kampala, Uganda, *Int. For. Rev.*, *11*(1), 64–78, doi:10.1505/ifor.11.1.64.

Oduor, N., J. Githiomi, and B. Chikamai (2006), *Charcoal Production using Improved Eartn , Portable Metal , Drum and Casamance Kilns*, Forest Pro., Kenya Forestry REsearch Institute, Nairobi. Kenya.

OEC (2020), Wood Charcoal Trade, *4402*. [online] Available from: https://oec.world/en/profile/hs92/wood-charcoal

Ozen, L. (2010), *Air pollution nuisance report*, Menashe Regional Council, Israel. [online] Available from: www.igudhadera.co.il

PCBS (2015), On the Eve of the International Day of Refugees, *Press Releases*. [online] Available from: http://pcbs.gov.ps/portals/_pcbs/PressRelease/Press_En_IntDyRef2015E.pdf

Peters, J. F., D. Iribarren, and J. Dufour (2015), Biomass Pyrolysis for Biochar or Energy Applications? A Life Cycle Assessment, *Environ. Sci. Technol.*, *49*, 5195–5202, doi:10.1021/es5060786.

Pósfai, M., A. Gelencsér, R. Simonics, K. Arató, J. Li, P. V Hobbs, and P. R. Buseck (2004), Atmospheric tar balls: Particles from biomass and biofuel burning, *J. Geophys. Res. Atmos.*, *109*(6), 1–9, doi:10.1029/2003jd004169.

Sweet Ankona, E., Tzadok, D., Elbaz, B., Atila Moskovitz, V., Litvak, I., Baranes, A., Gimburg, A., knup, Y., Billig, A., Anker, Y. (2018), Charcoal production emissions elimination, by assimilation of the new type of charcoal retort, in northern Samaria., *Samaria Res. Corpus, Vol. 27, No. 1*, 93-117. (in Hebrew).

Tintner, J., C. Preimesberger, C. Pfeifer, D. Soldo, F. Ottner, K. Wriessnig, H. Rennhofer, H. Lichtenegger, E. H. Novotny, and E. Smidt (2018), Impact of Pyrolysis Temperature on Charcoal Characteristics, *Ind. Eng. Chem. Res.*, *57*, 15613–15619, doi:10.1021/acs.iecr.8b04094.

Tomaselli, I. (2007), Forests and energy in developing countries, *For. Energy Work. Pap.*, 32.

UNDPE (2013), Nationally Appropriate Mitigation Action Study on Sustainable Charcoal in Uganda, *United Nations Dev. Program. (UNDP).*

United Nations (2006), *African Regional Implementation Review for the Commission on Sustainable Development (CSD-14) Report on the Review of African Sustainable Industrial Development*, Nairobi. [online] Available from: https://sustainabledevelopment.un.org/content/documents/ecaRIM_bp3.pdf

United Nations Environment Programme (UNEP) (2006), *African Regional Implementation Review for the 14th Session of the Commission on Sustainable Development (CSD-14): Report on Atmosphere and Air Pollution Prepared*, Nairobi, Kenya.

Yang, J.-F., C.-H. Yang, M.-T. Liang, Z.-J. Gao, Y.-W. Wu, and L.-Y. Chuang (2016), Chemical Composition, Antioxidant, and Antibacterial Activity of Wood Vinegar from Litchi chinensis, *Molecules*, *21*(9), 1150, doi:10.3390/molecules21091150.

Yatagai, M., M. Nishimoto, K. Hori, T. Ohira, and A. Shibata (2002), Termiticidal activity of wood vinegar, its components and their homologues, *J. Wood Sci.*, *48*(4), 338–342, doi:10.1007/BF00831357.

Yoshimoto, T. (1994), Present status of wood vinegar studies in Japan for agriculture usage., in *The 7th International Congress of the Society for the Advance of Breeding Researches in Asia and Oceania (SABRAO) and International Symposium of World Sustainable Agr*, pp. 811–820.