Pilot-Scale Evaluation of Concentrating Solar Thermal Technology for Essential Oil Extraction and Comparison with Conventional Heating Sources for Use in Agro-Based Industrial Applications

K. E. Manyako, Idan Chiyanzu, Jean Mulopo,* and Jibril Abdulsalam

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ABSTRACT: The conventional steam-distillation method requires a high amount of saturated steam and as a result, a lot of energy. Besides being energy-intensive, conventional steam-distillation processes emit carbon dioxide into the atmosphere. The energy demand in essential oils processing and related agro-based processes can be alleviated by using concentrating solar thermal (CST) technologies. Most of the solar plants installed in South Africa use flat plate collectors and evacuated tube collector systems with temperatures below 100 °C, which is ideal for only a low-temperature process application. This paper investigates the use of a low-cost CST technology, the parabolic trough collector (PTC), for steam-distillation in an extraction process. The PTC-powered system was built and tested for extracting essential oil from citrus peels. For comparison, the extraction process was carried out on a laboratory scale, a pilot gas-powered system, and PTC. Essential oil yields for orange, lemon, and mandarin were 0.65, 0.44, and 1.17%, respectively, using gas-powered steam-distillation. The yields for PTC were 0.67, 0.53, and 1.09%, which were all within the expected ranges. Gas chromatography results for the PTC experiment showed the presence of key components such as limonene (90%) in the essential oils. The PTC achieved a significant overall system efficiency of 54.99%, even though some parts of the device were not thermally insulated. The results showed that PTC can compete with gas-powered systems. Furthermore, the essential oil yields were comparable to those obtained in laboratory experiments. All of this demonstrates that PTC is suitable for use in agro-based industrial applications.

1. INTRODUCTION

The socio-economic development of any country is largely dependent on its energy sustainability. In many developing countries, the limited availability of primary energy sources combined with rising energy demand poses a serious threat to uninterrupted energy supply. Many developing countries' industrial and agricultural sectors have been impacted by the energy supply crisis. Furthermore, the environmental consequences of energy production from fossil-based sources, such as climate change, have a negative impact on the environment and public health. In this regard, there is an urgent need, particularly in developing countries, to explore alternative energy sources for a sustainable energy supply. Natural resources, such as solar energy, are an example of such viable alternatives.

Solar energy is by far the most promising and important energy resource currently available; it is an endless supply of energy with enormous exploitation potential across a wide range of industries and sectors. The average total irradiation near the equator is approximately 200−250 W m^{-2} day^{-1}.[1] This equates to approximately 1500−3000 h of sunlight, or 1.9−2.3 MW-h per annum.[2] This vast energy resource thus

provides an opportunity to harness it for agro-allied processes, particularly in developing countries, to reduce the environmental challenges associated with fossil-based energy sources. Most agro-based industrial processes, such as pasteurization, extraction, sterilization, drying, distillation, and so on, operate in the medium temperature range, with operating temperatures ranging between 60 and 280 °C.[1,3] As a result of the moderate temperature requirements in these processes, solar energy can be harnessed.

Essential oils are liquids containing volatile aroma compounds derived from plant materials that have found industrial applications in the production of perfumes, cosmetics, soap, shampoos, and cleaning gels. Another important application of essential oils is in the agro-food industry, where they are used to make beverages and flavor
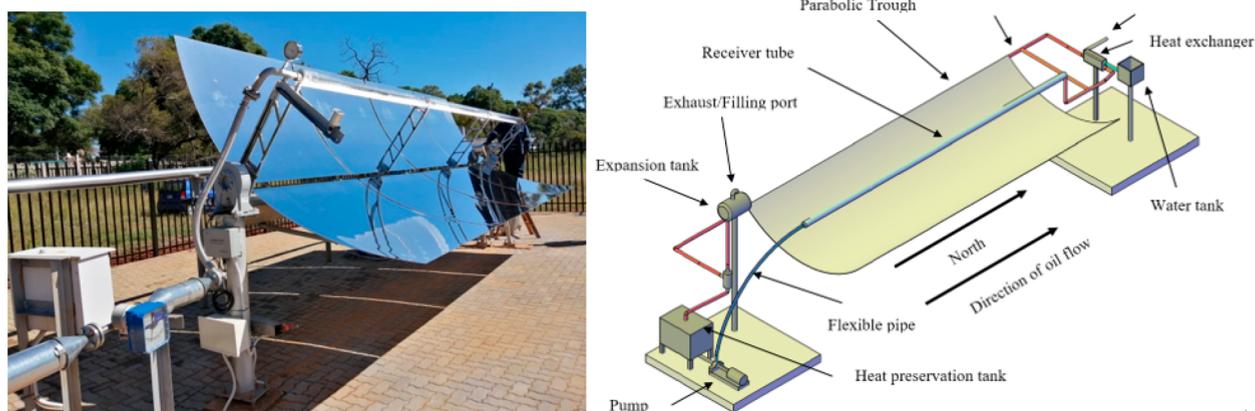
Figure 1. General view of experimental setup (left) and schematic diagram of fluid flow of the PTC-powered essential oil steam-distillation unit apparatus (southeast isometric view) (right).

foods.[4] Because of their fragrance, antioxidant, and antimicrobial properties, essential oils derived from aromatic plants and spices are highly valued in the pharmaceutical, food, and cosmetic industries.[5] The yield of essential oils from essential oil-bearing plants is typically between 0.005 and 10%.[6] Because essential oils are high-value products with low yields, it is important to use energy-efficient and sustainable technologies such as CST to improve the extraction process while lowering the carbon footprint, as opposed to the commercially accepted extraction method, distillation, which is energy-intensive.[5,7]

Distillation, which is used to extract clean and refined oil from plant materials by evaporating volatile compounds, is a key process unit in essential oil extraction. The majority of distillation processes use traditional energy sources, which consume a significant amount of energy.[8] Solar-powered distillation has been shown to reduce operating costs while increasing revenue by producing essential oils with minimal waste. Koul et al. developed a kinetic model to assess the batch extraction of essential oil from lemon grass using steam-distillation. According to the study, increasing the steam injection rate resulted in an increase in essential oil yield.[9]

In a CST system, solar radiation is concentrated onto a receiver and converted to thermal energy. A portion of the thermal energy is used to generate steam, which is then used to power a power cycle that generates electricity. A portion of the thermal energy can be stored in a thermal storage unit and used to power the cycle at night or when the weather is bad. As a result, a CST with a storage unit can balance fluctuating power generation, ensuring a dependable power system with a high proportion of renewables. This has resulted in a rapid rise in the global CST capacity in recent years, reaching 6430 MWe by December 2019.[10]

CST is classified as a parabolic trough collector (PTC), a flat plate collector (FPC), or an evacuated tube collector (ETC) depending on how solar radiation is collected.[11] FPC and ETC operate at temperatures below 100 °C and are primarily used to heat water, buildings, and swimming pools. There is research being done to raise the temperature of evacuated tube collectors and flat plate collectors, but despite efforts to improve them, these systems still cannot operate efficiently at high temperatures.[12,13] PTC is the most developed system, capable of reaching temperatures of up to 400 °C.[14] Smaller PTCs have been developed for process heat applications at temperatures less than 300 °C. These collectors have the potential to provide industrial process heat (IPH) to a variety

of applications, allowing them to eliminate the use of fossil fuels.[15]

Although CST technologies have a lot of potential in the agro-processing and industrial sectors, they have not been used as much as other solar thermal collectors for replacing fossil fuels and lowering carbon footprints.[3] The potential use of CST technology, specifically the parabolic trough collector, for essential oil extraction is explored in this paper. In addition, for comparison, both laboratory steam-distillation and gas-powered steam-distillation were used. Citrus peels were used as a feedstock for the extraction process, including orange, lemon, and mandarin.

2. MATERIALS AND METHODS

2.1. Feed Sample Analysis. The feed sample was dried at 135 °C for 2 h in accordance with the AOAC Official Methods 930.15. It is one of the commonly used methods for feed moisture analysis due to its ease of use.[16] For ash content, the feedstock material was tested based on the prescribed conditions of AOAC Official Methods 942.05; the test ran for 2 h at a temperature of 600 °C. The protein content was determined by using AOAC Official Method 954.01, whereby the feedstock samples are digested with sulfuric acid to convert amino groups of protein to ammonia which is distilled into a boric acid receiver and measured by titration with a sulfuric acid solution. The nitrogen content was multiplied by a universal factor of 6.25 to obtain the protein content.[17] For fat content analysis, a traditional organic solvent method, called SOXTEC SYSTEM was used. During the extraction process, fat is dissolved in the solvent inside the extraction unit, after which, the solvent is vaporized from the extraction cup and passes through the condenser leaving the fat behind. Diethyl was used in the process. AOAC Official Methods 978.10, which uses a fritted glass crucible, was used for crude fiber. The method was conducted by extracting the feed material with acid and alkali.[17] Carbohydrates were calculated from the known dry matter, protein, fat, and ash content.[18] It was agreed to use detergents in the feed analysis.

Neutral detergent fiber (NDF) was determined by using an NDF method, which was based on the extraction of feed with a hot neutral solution of sodium lauryl sulfate.[19] Acid detergent fiber (ADF) was determined by using the ADF method, the method used heat treatment of the sample with sulfuric acid containing cetyltrimethylammonium bromide.[20] Acid detergent lignin (ADL) is determined by treating the ADL residue

with 72% sulfuric acid.[20] The difference between NDF and ADF values gives an estimate of the content of noncellulosic polysaccharides. The ADF residue contains mainly cellulose and lignin. The lignin content was determined and the resulting residue gave the cellulose content. NDF = lignin + cellulose + hemicellulose, ADF = lignin + cellulose, ADL = acid detergent lignin, NDF − ADF = hemicellulose and ADF − ADL = cellulose. The essential oil was analyzed using gas chromatography (GC) to determine the fatty acid profile.

2.2. Extraction Equipment. *2.2.1. Solar Extraction Setup.* Experimental setup consists of a 6 m long PTC, a single-axis tracking system, a plate heat exchanger (PHE), and a steam-distillation pot as shown in Figure 1. PTC consists of a steel frame, which supports the mirrors in a parabola shape. Parabolic mirrors with a specular reflectance of more than 92% have an aperture width of 2.55 m and are made of 1 mm silver tempered glass covered by a layer of highly reflective silver coating. An evacuated tube-type receiver with a vacuum degree of 3.0×10^{-4} Pa (at 200 °C) absorbs reflected solar radiation from the mirrors. Thermal energy is carried away from the receiver by the heat transfer fluid (HTF); therminol 66, which transfers heat from the receiver to the PHE. Three key parameters, volumetric flow rate, collector inlet, and outlet temperature were recorded and used to calculate the net thermal energy output using eq 1:

$$\dot{Q}_c = \dot{m}c_p(t_o - t_i) \tag{1}$$

$\dot{Q}_c$ is the net thermal energy output, $\dot{m}$ is the mass flow rate through the collector which is determined by multiplying the volumetric flow rate by the temperature-dependent density ρ, c_p is the specific heat capacity of the HTF which is also temperature-dependent, t_o and t_i are the collector outlet and inlet temperatures, respectively.[14] Experiments were carried out between 9 a.m. and 3 p.m. on a sunny day. The prediction models listed below apply to therminol 66 and were used to calculate net thermal energy output, where T is the temperature of the HTF:[21]

$$\rho = -0.614254T(°C) - 0.000321T^2(°C) + 1020.62 \tag{2}$$

$$c_p = 0.003313T(°C) + 0.0000008970785T^2(°C) + 1.496005 \tag{3}$$

Another important part of the experimental setup is the distillation pot, which is cylindrical in shape, made of stainless steel 304, with a diameter of 207 mm, a height of 502 mm, and a thickness of 2 mm. The distillation pot receives the saturated steam produced by the PTC system. A perforated grill is built into the distillation pot to provide a bed for plant material. At the bottom of the distillation pot, one pressure gauge and one temperature gauge were installed, while one temperature gauge was installed near the top. The sealable lid is 6 mm thick and has a seal. A condenser is attached to the distillation pot and is used to condense the vapors. For thermal analysis of the distillation tank, the inlet and outlet temperature of the tank was recorded and used during the calculations of heat losses on the vertical, bottom, and top walls of the distillation pot. The overall efficiency of the PTC-powered system was calculated as the product of the PTC, distillation pot, and heat exchanger efficiency.

The potential solar radiation at the selected site for the PTC experiment is shown in Table 1. The solar potential of any CSP

Table 1. Solar Resource Potential at the Selected Site for PTC Experiment

location	Cresswell Road. Pretoria. Gauteng 0184. South Africa
geographical coordinates	−25.729533°. 28.276100° (−25°43′46″. 28°16′34″)
time zone	UTC+02. Africa/Johannesburg
direct normal irradiation	2138 kWh/m^2/year
global horizontal irradiation	2023 kWh/m^2/year
diffuse horizontal irradiation	659 kWh/m^2/year

project is heavily influenced by the direct normal irradiation (DNI) at the installation site. As shown in Table 1, DNI was extracted from Global Solar Atlas, a solar irradiation database, along with other important data. According to the Global Solar Atlas maps, the selected site receives a DNI of 2138 kWh/m^2 per year. Table 2 shows the average monthly DNI data as generated from the Global Solar Atlas.

Table 2. Determination of Annual Average Instantaneous DNI (2020)

month	average sunshine hours per day (hours)	number of days per month (d/m)	hours in a month (h × d/m)	average direct solar irradiation (kwh/m^2/day)
January	8.4	31	260.4	5.53
February	8.4	28	235.2	5.53
March	8.2	31	254.2	5.40
April	8.2	30	246	5.40
May	9.1	31	282.1	5.99
June	9	30	270	5.93
July	9.3	31	288.3	6.13
August	9.5	31	294.5	6.26
September	9.5	30	285	6.26
October	8.9	31	275.9	5.86
November	8.5	30	255	5.60
December	8.8	31	272.8	5.80
total sunshine hours		3219.4		
long-term average DNI		2138		
annual average instantaneous DNI		664.10		

The thermal efficiency of the collector can be expressed by the following equation

$$\eta_t = \frac{\dot{Q}_s}{\dot{Q}_c} \tag{4}$$

where η_t is thermal efficiency of the collector, $\dot{Q}_s$ is the solar energy flux incident on the collector aperture plane, and $\dot{Q}_c$ is the net thermal output power delivered by the collector.

The solar energy flux incident on the collector aperture plane and the Net thermal output power delivered by the collector is expressed by the following equations:

$$\dot{Q}_s = A_a G_B \cos\varphi \tag{5}$$

$$\dot{Q}_c = \dot{m}c_p(t_o - t_i) \tag{6}$$

where A_a is the aperture area of the collector, G_B is the direct beam solar irradiance, φ is the incidence angle of the collector, $\dot{m}$ is the mass flow rate through the collector which is

determined by multiplying the volumetric flow rate by the temperature-dependent density, c_p is the specific heat capacity of the HTF which is also temperature-dependent, t_o and t_i are the collector outlet and inlet temperatures, respectively. The net thermal output can also be expressed by eq 6 below:

$$\dot{Q}_c = F_R[G_B\eta_o A_a - A_r U_L(t_i - t_a)] \tag{7}$$

F_R is the heat removal factor, η_o is the optical efficiency, A_r is the surface area of the receiver, U_L is the overall heat loss coefficient of the collector, and t_a is the ambient temperature. From eq 7, the product of the U_L and the difference between the t_i and t_a, represent the thermal energy loss through the collector to the surroundings. This thermal energy is lost through conduction, convection, and infrared radiation.

The thermal efficiency can be determined by dividing eq 7 by $G_B A_a$

$$\eta_t = F_R\left[\eta_o - U_L\left(\frac{t_i - t_a}{G_B C}\right)\right] \tag{8}$$

where C is the concentration ratio, expressed as $C = A_a/A_r$.

When operating under steady-state conditions, the parameters F_R, U_L, and η_o are nearly constant, given the steady-state conditions of the solar irradiation and mass flow rate of the heat transfer fluid (HTF). A plot of η_t against $(t_i - t_a)/G_B C$ is a straight line, with a y-intercept of $U_L\eta_o$ and a gradient of $F_R U_L$. The gradient is an indication of how much energy has been removed from the solar collector, whereas the y-intercept denotes the maximum collector efficiency at which the inlet temperature t_i is equivalent to the ambient temperature.

The heat removal factor is obtained from the following equation:

$$F_R = \frac{\dot{m}c_p}{A_r U_L}\left[1 - \exp\left(\frac{U_L F' A_r}{\dot{m}c_p}\right)\right] \tag{9}$$

where F' is the collector efficiency factor, which is computed from the following equation:

$$F' = \frac{1/U_L}{\frac{1}{U_L} + \frac{D_o}{h_{fi}D_i} + \left(\frac{D_o}{2k}\ln\frac{D_o}{D_i}\right)} \tag{10}$$

where D_o and D_i are the receiver outside tube diameter and receiver inside tube diameter, respectively; h_{fi} is the convective heat transfer coefficient inside the receiver tube. The efficiency was calculated by using eq 4, therefore

$$\eta_t = \frac{\dot{m}c_p(t_o - t_i)}{A_a G_B \cos\varphi} \tag{11}$$

The calculation of the net thermal output or useful energy requires a measurement of the inlet temperature and outlet temperature, as well as the volumetric flow of the HTF, which is multiplied by the density to determine the mass flow rate. Measured temperatures are used to determine the temperature-dependent thermal properties, which are in turn used to calculate the useful energy.

The total rate of heat transfer into the distillation tank is given by the amount of energy required to reach saturated conditions plus the amount of energy required to vaporize oil and water. The energy consumed by the distillation tank in KJ is the sum of sensible heat energy and latent heat of vaporization, therefore eq 12 represents the rate of heat

transfer, whereby the first term in the numerator is the sum of sensible heat energy and the second term is the latent heat of vaporization.

$$E_t = \frac{[\{M_p m_p c_w + m_d c_s + m_p(1 - M_p)c_f\}\Delta T + M_p m_p h_w]}{t} \tag{12}$$

E_t is the total heat transfer rate into the distillation tank, M_p is the moisture content of the plant material (wet basis), m_p is the mass of the plant material, c_w is the specific heat capacity of water, m_d is the mass of the distillation tank, c_s is the specific heat capacity of stainless steel, c_f is the specific heat capacity of fiber, ΔT is the change in temperature, and h_w is the latent heat of vaporization of water at atmospheric pressure. t is the time taken to reach saturated conditions.

The overall energy balance of the solar-powered essential oil steam-distillation unit can be expressed as

$$E_t = E_u + E_l \tag{13}$$

where E_t is the input energy into the distillation tank, E_u is the useful energy directed to the essential oil extraction process, E_l is the heat losses through the walls of the distillation tank. The efficiency of the distillation tank was calculated as

$$\eta_{still} = \frac{E_u}{E_t} \tag{14}$$

The overall efficiency of the whole system is given as the product of the thermal efficiency of the distillation tank and the thermal efficiency of the collector, thus the following equation applies:

$$\eta_o = \eta_{distillation\ tank} \times \eta_{collector} \tag{15}$$

For ease of calculation of energy output and losses in the solar-powered steam-distillation, a Microsoft Excel model was developed to estimate the thermal output of the solar collector and input energy to the distillation tank, as well as the losses on the walls of the distillation tank.

2.2.2. Laboratory Distillation Setup. Further steam-distillation experiments were conducted by using a laboratory glassware apparatus and liquefied petroleum gas (LPG) powered steam-distillation unit (Figure 2). In the case of laboratory experiments, a 2.75 kW portable gas (butane) stove was used to provide heat to a one liter flask carrying water for steam generation. The net weight of butane gas after each laboratory experiment was used to quantify both the rate of heat transfer and power consumption, whereas the net weight

Figure 2. General view of laboratory and field gas-powered steam-distillation of essential oils.

of LPG after each gas-powered steam-distillation experiment was used to quantify heat used in kWh as well as the rate of heat in kW. The rate of heat was determined by dividing the total energy used by the distillation time.

2.3. Methods. Citrus peels have been the subject of several laboratory studies. Many factors that determine the efficiency of the distillation process, distillation temperatures, essential oil quality, and yield, were observed during the experiments. For all laboratory experiments, parameters such as butane gas consumption, citrus peels weight before and after distillation, heating time, extraction vessel temperature, the quantity of hydrosol, essential oil, and water in the flask before and after steam generation were recorded. The calculated data yielded a variety of useful details. For each experiment, a clock watch was started and stopped when the oil column in the separator funnel was almost constant, and an average distillation time was determined for each citrus peel. The inlet and outlet temperatures of the distillation pot were recorded in gas-powered and PTC-powered experiments, and other parameters similar to those recorded in the laboratory experiment, that is, citrus peels weight before and after distillation, heating time, distillation temperature, the quantity of hydrosol, essential oil, and LPG consumption for the gas-powered field experiment.

3.0. RESULTS AND DISCUSSION

3.1. Analysis of Feed Samples. The dry matter, ash, total solids, moisture contents, and composition of fresh citrus peels are shown in Tables 3 and 4.

Table 3. Dry Matter, Ash, Total Solids, Moisture Contents of Fresh Citrus Peels

analysis	method number	fresh citrus peels before distillation		
		orange peels	lemon peels	mandarin peels
dry matter (%)	ASM013	86.83	86.92	83.41
ash (%)	ASM 048	3.41	3.69	2.43
total solids (%)		83.42	83.23	80.98
moisture (%)	ASM 013	13.17	13.08	16.59

Table 4. Composition of Fresh Citrus Peels

analysis (%)	method number	fresh citrus peels before distillation		
		orange peels	lemon peels	mandarin peels
protein ($N \times 6.25$)	ASM 078	10.49	4.88	5.9
fat (ether extraction)	ASM 044	1.42	1.17	1.4
carbohydrates (calculated)	ASM 075	71.51	77.18	73.68
total nonstructural carbohydrates	ASM 073	41.35	33.05	45.07
fiber (crude)	ASM 059	11.57	12.27	8.1
neutral detergent fiber	ASM 060	15.2	18.28	10.37
ADF		16.12	14.94	10.16
ADL		0.71	1.09	0.48
cellulose		15.41	13.85	9.68
hemicellulose		−0.92	3.34	0.21

3.2. System Power Supply and Power Consumption. The energy consumption for individual field experiments for the gas-powered system ranged from 3.562 to 4.834 kWh for orange, with an average of 4.41 kWh, 2.544 to 4.58 kWh for lemon, with an average of 3.307 kWh, and 3.181 to 4.834 kWh for mandarin, with an average of 4.198 kWh (Figure 3). On the
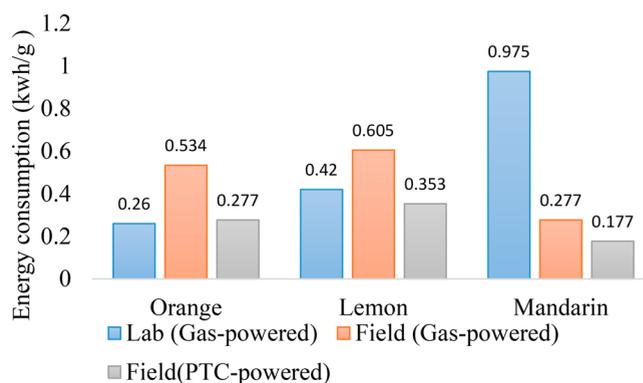
Figure 3. Energy consumption per gram of oil produced.

other hand, the energy consumption for individual field experiments for PTC-powered systems was 2.348 to 2.46 kWh for orange, with an average of 2.387 kWh, 2.376 to 2.497 kWh for lemon, with an average of 2.417 kWh, and 2.424 to 2.554 kWh for mandarin, with an average of 2.506 kWh. From the PTC-powered experiments, it was observed that the thermal energy supply sufficient for steam-distillation was maintained as if the experiment was conducted by using gas as a fuel, as long as there was sufficient sunshine. To maintain a sufficient power supply to the steam-distillation process, a steady power supply (rated in kW) must be available and maintained throughout the extraction process, thus promoting high-quality essential oils. For laboratory experiments, the rates of heat transfer into the system were 2.15, 1.94, and 2.08 kW, for orange, lemon, and mandarin, respectively. The incremental changes of mass loading (50 g) of the feedstock for distillation did not show significant changes in input energy required; however, for large amounts of plant material, high amounts of input energy were required. This is needed because larger amounts of sensible energy and latent heat of vaporization will be required as the mass of moisture in the plant material and the mass of essential oil increase. The heat transfer rate delivered by the field gas-powered experiments was estimated to be 7.201, 5.336, and 7.857 kW for orange, lemon, and mandarin, respectively. The PTC supplied 12.704 kW; some of this heat was reserved in the heat preservation tank of the system and the net energy was directed to the steam-distillation of essential oils through a heat exchanger. PTC-powered steam-distillation reached the highest temperature of 295 °C, with the maximum bulk temperature (345 °C) of the therminol 66 being the only limiting factor to reaching even higher temperatures. Taking the thermal efficiency of the distillation pot, PTC, and PHE into account, the overall efficiency of the PTC-powered steam-distillation setup was determined to be 54.99%, while the overall efficiency of the field gas-powered experiment was found to be 70.5%. The efficiency of 70.5% did not however consider the fact that the gas-fired boiler was without insulation, therefore an efficiency value of less than 70.5% will be more realistic.

3.3. Essential Oil Yields, Efficiency of Solar Distillation, and Essential Oil Quality. The yields of orange, lemon, and mandarin essential oils were found to be 0.67, 0.53, and 1.09% for PTC, whereas for gas-powered steam-distillation, the yields were 0.65, 0.44, and 1.17% for orange, lemon, and mandarin peels, respectively (Figure 4). The results of orange and lemon indicated a 3%, and 20% decrease, respectively, in oil yield when moving from gas-powered
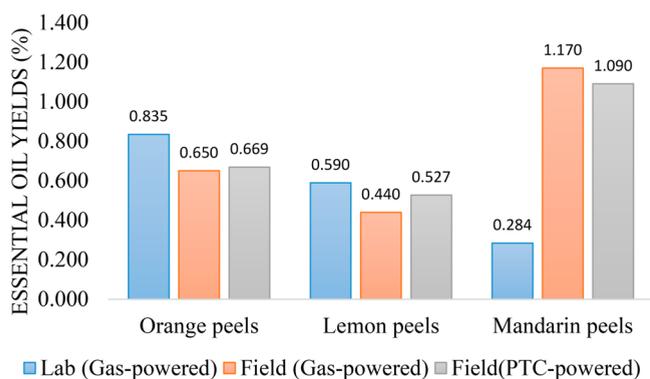
Figure 4. Essential oil yields.

experiments to PTC-powered experiments, whereas in the case of mandarin, the change from gas to PTC-powered experiments produced a slightly opposite result, which is an 8% drop in oil yield when changing from gas to PTC-powered experiments. The yields for orange and mandarin peels for the PTC-powered experiments are within the ranges found in the literature. However, with lemon, the yield was a little lower than the expected range (0.6−1%), and the same trend continued with the gas-powered experiment.[22] Comparison of the laboratory results and PTC-powered steam-distillation showed relatively higher yields for laboratory experiments, thus showing a need for improvement of the field experiments. With regards to energy consumption per gram of oil produced (efficiency of distillation), when comparing field gas-powered experiment and field PTC-powered experiment, it can be seen that the distillation pot used less power when powered by a

Table 5. Orange Peels Chemical Compositions

chemical compound	orange experiments		
	lab (gas-powered)	field (gas-powered)	PTC-powered
linalyl propionate	1.21		
DL-limonene	75.3	1.79	
linalool	1.79	2.67	
p-mentha-E-2,8(9)-dien-1-ol	1.09		
1-nonanol (CAS)	1.21		1.42
nerol (CAS)	4.14		
1-decanol (CAS)	3.28		
geranyl acetate	1.01		
dodecanal (CAS)	1.22		
naphthalene, 1,2,3,5,6,7,.8.8a-octahydro-1,8a-dimethyl-7-(1-methylethenyl)-, [1R-(1,alpha.,7.β.,8a.alpha.)]-	1.78		
D-limonene		1.57	
cycloheptene, 5-ethylidene-1-methyl- (CAS)		1.44	
cyclobutane, 1,2-bis(1-methylethenyl)-, trans- (CAS)		1.68	
cis-2-(2-pentenyl)furan		2.44	
1,5-cyclooctadiene, 1,5-dimethyl-		1.7	
D-limonene		1.16	
β-terpinyl acetate		1.24	
cyclobutane, 1,2-diethenyl-3-methyl- (CAS)		1.95	
bicyclo[2.2.1]heptane, 2-(1-methylethenyl)-		1.14	
cyclohexene, 1-methyl-5-(1-methylethenyl)-		0.98	
sabinene	0.03		
limonene oxide		1.46	2.08
β-sinensal	0.44		0.19
citronella		0.99	2.35
3-cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)- (CAS)		1.3	
decanal (CAS)		3.25	12
nerol (CAS)		2.4	
6-octen-1-ol, 3,7-dimethyl-, (R)-		1.86	
Z-citral		2.83	3.91
2-cyclohexen-1-one, 2-methyl-5-(1-methylethenyl)-, (S)- (CAS)		1.08	1.49
geraniol		3.27	
2-propenoic acid, 2-methyl-, decyl ester (CAS)		4.61	

chemical compound	orange experiments		
	lab (gas-powered)	field (gas-powered)	PTC-powered
undecanal (CAS)		0.96	
geranyl acetate		1.36	
L-linalool			3.44
3-cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)- (CAS)			1.88
3-cyclohexene-1-methanol,.alpha.,.alpha.,4-trimethyl-, (S)- (CAS)			1.09
α-pinene	0.11		
carveol 1			1.49
2,6-octadien-1-ol, 3,7-dimethyl- (CAS)			5.83
trans-geraniol			4.5
1-decanol (CAS)			6.56
1-cyclohexene-1-carboxaldehyde, 4-(1-methylethenyl)-, (S)-			1.4
undecanal (CAS)			1.3
neryl acetate			1.77
2,6-octadien-1-ol, 3,7-dimethyl-, acetate, (Z)-			2.24
β-elemene			2.16
dodecanal (CAS)			1.38
trans-caryophyllene			2.95
trans-caryophyllene			2.73
naphthalene, 1,2,3,5,6,7,8,8a-octahydro-1,8a-dimethyl-7-(1-methylethenyl)-, [1R-(1.alpha.,7.β.,8a.alpha.)]-			2.7
naphthalene, 1,2,3,5,6,7,8,8a-octahydro-1,8a-dimethyl-7-(1-methylethenyl)-, [1R-(1.alpha.,7.β.,8a.alpha.)]-			5.64
valencene (CAS)			
(−)-caryophyllene oxide			1.85
dodecanal (CAS)			2.13
bicyclo[5.2.0]nonane, 2-methylene-4,8,8-trimethyl-4-vinyl-			1.46
trans-caryophyllene			2.01
valencene (CAS)			1.16
valencene (CAS)			4.96
valencene (CAS)			4.18
(−)-caryophyllene oxide			1.49
(1S,4aS,7R,8aS)-1,4a-dimethyl-7-(prop-1-en-2-yl)decahydronaphthalen-1-ol			0.59

PTC. This can be attributed to the fact that during a hot sunny day, the distillation pot was relatively hot, thus requiring less energy to raise the stainless steel and the pot contents to 100 °C. With regards to oil quality, PTC experiments showed the presence of the important main components; for example, mandarin peels had 90.24% limonene. There were also other components appearing in significant amounts. The components included 1.3% β-myrcene and l.8% linalool in mandarin peels, 2.45% (−)-β-pinene, 2.15% γ-terpinene, 1.95% β-bisabolene, and 5.55% geranyl acetate for lemon peels, 3.44% L-linalool, 12% decanal, and 2.35% citronella for orange peels.

Tables 5, 6, and 7 show the chemical compositions appearing in three citrus fruits peels. The primary chemical

Table 6. Lemon Peels Chemical Compositions

| chemical compound | lemon experiments | | |
	lab (gas-powered)	field (gas-powered)	PTC-powered
(−)-β-pinene	2.39	2.54	2.45
β-myrcene	1.63		
2-β-pinene	0.91		
2-β-pinene	0.93		
1,5-cyclooctadiene, 1,6-dimethyl-	54.97	55.34	56.46
1,5-cyclooctadiene, 1,6-dimethyl-	6.15		
γ-terpinene	2.17	2.23	2.15
1,6-octadien-3-ol, 3,7-dimethyl-	1.07		
limonene oxide	1.39		
3-cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-	1.24		1.33
3-cyclohexene-1-methanol,.alpha.,.alpha.,4-trimethyl-, (S)- (CAS)	1.59	1.63	1.82
nerol (CAS)	3.06		3.61
sabinene	0.66	0.93	
trans-geraniol	3.2		3.68
undecanal (CAS)	0.9		0.95
neryl acetate	2.26		
geranyl acetate	1.18	5	5.55
2-β-pinene	0.91		
caryophyllene	1.59		
valencene (CAS)	1.25		2.18
β-bisabolene (CAS)	1.63	1.79	1.95
isomyrcenyl acetate		1.14	
α-terpinolene		1.11	1.12
citronella		1.19	
isogeranial		1.03	
Z-citral		3.35	
3,7-dimethyl-2,6-octadienal		3.32	
trans-caryophyllene		2.1	
naphthalene, 1,2,3,5,6,7,8,8a-octahydro-1,8a-dimethyl-7-(1-methylethenyl)-, [1R-(1.alpha.,7.beta.,8a.alpha.)]-		1.94	
cis-(−)-1,2-epoxy-p-menth-8-ene			1.11
CIS-caryophyllene			1.99
cis-alpha-bergamotene			1.07
bicyclo[3.1.1]heptane, 6,6-dimethyl-2-methylene-, (1S)-			0.9

Table 7. Mandarin Peels Chemical Compositions

| chemical compound | mandarin experiments | | |
	lab (gas-powered)	field (gas-powered)	PTC-powered
β-myrcene	0.93		1.34
DL-limonene	60.06	0.68	90.24
7-oxabicyclo[4.1.0]heptane, 1-methyl-4-(1-methylethenyl)-	1.97		
decanal (CAS)	2.08	7.45	
spiro[4.5]dec-6-en-8-one, 1,7-dimethyl-4-(1-methylethyl)-	1.23		
D-carvone	1.67		
1-decanol	1.2		
1,4-cyclohexadiene, 1-methyl-4-(1-methylethyl)-		5.17	
3,4-dimethylbenzyl alcohol		1.57	
linalool		5.31	1.18
limonene oxide		1.08	
1-nonanol (CAS)		1.15	
3-cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-, (R)-		1.53	
6-octen-1-ol, 3,7-dimethyl-, (R)-		2.79	
Z-citral		1.2	
2-cyclohexen-1-one, 2-methyl-5-(1-methylethenyl)-, (S)- (CAS)		1.15	
2-decenal, (E)- (CAS)		1.81	
1-decanol (CAS)		3.57	
1-cyclohexene-1-carboxaldehyde, 4-(1-methylethenyl)-, (S)-		2.42	
p-mentha-1(7),8(10)-dien-9-ol		2.73	
undecanal (CAS)		2.21	
2,4-decadienal, (E, E)- (CAS)		0.92	
(−)-cis-isopiperitenol acetate		1.06	
trifluoroacetyl-lavandulol		1.58	
neryl acetate		3.61	
α-cubebene		2.72	
geranyl acetate		2.91	
β-elemene		3.51	
α-pinene, (−)-		0.1	
dodecanal (CAS)		3.55	
limonen-10-yl acetate		2.22	
trans-caryophyllene		2.18	
p-mentha-1,8-dien-7-yl acetate		1.37	
(1S,5S,6R)-6-methyl-2-methylene-6-(4-methylpent-3-en-1-yl)bicyclo[3.1.1]heptane		3.82	
(1S,5S,6R)-6-methyl-2-methylene-6-(4-methylpent-3-en-1-yl)bicyclo[3.1.1]heptane		1.3	
germacrene-D		1.2	
valencene (CAS)		1.26	
naphthalene, 1,2,3,4,4A,5,6,8A-octahydro-7-methyl-4-methylene-1-(1-methyl ethyl)-, (1. α.,4A. α.,8A. α.)-		1.02	
farnesene (CAS)		5.59	
farnesene (CAS)		1.85	
8-isopropyl-1,3-dimethyltricyclo[4.4.0.0−2.7∼]dec-3-ene		3.21	
cadinene		0.96	
γ-terpinene		1.87	

components of orange, lemon, and mandarin peels were found in large concentrations in the majority of cases, demonstrating that solar systems may be used to extract essential oils. For example, in the steam-distillation of mandarin peels, the PTC-powered system had much higher limonene component concentrations than all other tests. According to Ameh and Obodozie-Ofoegbu, i-limonene is prevalent in citrus essential oils, therefore traces of large concentrations of it are essential in steam-distillation as it is utilized for aroma and flavoring in

the agro-food industry.[23] Other important citrus peel components, on the other hand, were also successfully extracted. They are as follows: linalool, geranyl acetate, sabinene, β-sinensal, decanal (CAS), γ-terpinene, β-myrcene, d-carvone, neryl acetate, and citronella. The majority of these chemical components were found to be in high concentrations, which is required to maintain the defining and crucial properties of citrus peel essential oil. Citral, linalool, decanal, and β-sinensal are important aroma-active ingredients in the formulation of citrus essential oils for the cosmetic and fragrance industries, therefore their occurrence in the extracted citrus essential oil was a significant achievement.[24] It is noteworthy that most of the major components (γ-terpinene, myrcene, sabinene, neryl acetate, β-bisabolene, linalool) reflected in PTC-powered pilot experiments also appear in the laboratory and gas-powered experiment. These common compounds found in different citrus peel essential oils account for similar aromas. The differences in concentrations of each compound account partly for the dissimilarities.[24]

3.4. Environmental Impact of Conventional Extraction Methods. A total of 800 g of CO_2 is released when burning fossil fuels generating heat energy of 1 kWh.[21] To investigate the impact of CO_2 emissions, the CO_2 emissions for every gram of oil produced were calculated for the gas-powered experiment. The CO_2 emissions were found to be 472.2, 484, and 221.6 g for orange, lemon, and mandarin, respectively. It should be taken into consideration that, although CO_2 emissions are in the range of grams, it takes more energy and more plant material to produce one gram of oil, thus producing more CO_2 emissions. To further show the extent of CO_2 emissions and negative impact on the environment, a few experiments were arbitrarily selected from the recorded experimental data of total kWh consumed during extraction using gas as a heat source. The CO_2 emissions were found to be 3.9, 2.2, and 2.5 kg for orange, lemon, and mandarin, respectively. The experiments took between 30 and 40 min but each produced CO_2 emissions in the range of kilograms. This shows how conventional extraction methods can affect the environment. The amount of total energy and CO_2 emissions can appreciably be higher, depending on which plant material is extracted. Certain plants consume more energy on a per gram basis, and as a result, more CO_2 is emitted into the atmosphere. For example, it has been reported that conventional extraction methods such as water distillation consumed more than 6.5 kWh total energy when extracting vetiver oil and that the production of patchouli oil on a per gram of oil resulted in an energy consumption of 6.55 kWh when extracted with water distillation.[19] That is an equivalent of 5.24 kg of CO_2 emissions for every gram of essential oil produced. These are substantial amounts of both energy and harmful CO_2 emissions, which can be mitigated by solar energy.

4. CONCLUSION

The PTC-integrated steam-distillation unit was designed and tested experimentally in this study to determine whether this type of CST device can successfully be used for steam-distillation of essential oils in the agro-based industry. Three experiments were carried out, namely a laboratory test and two field tests involving gas and PTC-driven steam-distillation. Low-pressure, PTC-powered steam-distillation was successfully operated, reaching a temperature of 295 °C and giving yields of orange, lemon, and mandarin essential oils of 0.67, 0.53, and

1.09%, respectively, while the yields of orange, lemon, and mandarin peels were 0.65, 0.44, and 1.17%, respectively, for gas-driven steam-distillation. The results were also compared in terms of energy efficiency. The average performance of the gas-powered steam-distillation experiment was 70.4%, with the possibility of even lower efficiency due to the boiler's lack of thermal insulation. The overall device efficiency of the PTC-powered steam-distillation, on the other hand, was found to be 54.99% which is 15.41% less than the gas-powered steam-distillation. Although the overall device efficiency is relatively low, it still compares favorably to that of other related research studies, and in some cases is even higher.

■ AUTHOR INFORMATION

Corresponding Author

    Jean Mulopo − *School of Chemical and Metallurgical Engineering, University of Witwatersrand, Johannesburg 2050, South Africa;* ⊙ orcid.org/0000-0001-9786-6799; Email: jean.mulopo@wits.ac.za

Authors

    K. E. Manyako − *Agricultural Research Council-Agricultural Engineering (ARC-AE), Pretoria 0001, South Africa; School of Chemical and Metallurgical Engineering, University of Witwatersrand, Johannesburg 2050, South Africa*

    Idan Chiyanzu − *Agricultural Research Council-Agricultural Engineering (ARC-AE), Pretoria 0001, South Africa*

    Jibril Abdulsalam − *School of Chemical and Metallurgical Engineering, University of Witwatersrand, Johannesburg 2050, South Africa;* ⊙ orcid.org/0000-0001-5072-4996

Complete contact information is available at:
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Notes

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■ REFERENCES

(1) Afzal, A.; Munir, A.; Ghafoor, A.; Alvarado, J. L. Development of hybrid solar distillation system for essential oil extraction. *Renew. Energy.* **2017**, *113*, 22−29.

(2) Khan, N. A.; Mirza, I. A.; Khalil, M. S. *Renewable energy in Pakistan: status and trends*; Alternative Energy Development Board (AEDB): 2014.

(3) Kalogirou, S. The potential of solar industrial process heat applications. *Appl. Energy.* **2003**, *76* (4), 337−361.

(4) Rios, J. L. Essential oils: What they are and how the terms are used and defined. In *Essential oils in food preservation, flavor and safety*; Academic Press: New York, 2016; pp 3−10.

(5) Valderrama, F.; Ruiz, F. An optimal control approach to steam distillation of essential oils from aromatic plants. *Comput. Chem. Eng.* **2018**, *117*, 25−31.

(6) Phi, N. T. L.; Hung, P. V.; Chi, P. T. L.; Dung, N. H. Impact of extraction methods on antioxidant and antimicrobial activities of citrus essential oils. *J. Essent. Oil-Bear. Plants.* **2015**, *18* (4), 806−817.

(7) Häberle, A. Concentrating solar technologies for industrial process heat and cooling. In *Concentrating Solar Power Technology*; Woodhead Publishing: 2012; pp 602−619.

(8) Okoro, O. I.; Madueme, T. C. Solar energy investments in a developing economy. *Renew. Energy.* **2004**, *29* (9), 1599−1610.

(9) Koul, V. K.; Gandotra, B. M.; Koul, S.; Ghosh, S.; Tikoo, C. L.; Gupta, A. K. Steam distillation of lemon grass (Cymbopogon spp.). *Ind. J. Chem. Technol.* **2004**, *11*, 135.

(10) He, Y. L.; Qiu, Y.; Wang, K.; Yuan, F.; Wang, W. Q.; Li, M. J.; Guo, J. Q. Perspective of concentrating solar power. *Energy* **2020**, *198*, 117373.

(11) He, Y. L.; Xiao, J.; Cheng, Z. D.; Tao, Y. B. A MCRT and FVM coupled simulation method for energy conversion process in parabolic trough solar collector. *Renew. Energy.* **2011**, *36* (3), 976−985.

(12) Kalogirou, S. A. Building integration of solar renewable energy systems towards zero or nearly zero energy buildings. *Int. J. Low Carbon Technol.* **2015**, *10* (4), 379−385.

(13) Moya, E. Z. Parabolic-trough concentrating solar power (CSP) systems. In *Concentrating solar power technology*; Woodhead Publishing: 2012; pp 197−239.

(14) Vignarooban, K.; Xu, X.; Wang, K.; Molina, E. E.; Li, P.; Gervasio, D.; Kannan, A. M. Vapor pressure and corrosivity of ternary metal-chloride molten-salt based heat transfer fluids for use in concentrating solar power systems. *Appl. Energy.* **2015**, *159*, 206−213.

(15) Ahn, J. Y.; Kil, D. Y.; Kong, C.; Kim, B. G. Comparison of oven-drying methods for determination of moisture content in feed ingredients. *Asian-australas. J. Anim. Sci.* **2014**, *27* (11), 1615.

(16) Greenfield, H.; Southgate, D. A. *Food composition data: production, management, and use: Food and Agriculture Organization*; Springer: 2003.

(17) Blok, C.; Baumgarten, A.; Baas, R.; Wever, G.; Lohr, D. Analytical methods used with soilless substrates. In *Soilless Culture*; Elsevier: 2019; pp 509−564.

(18) Goering, H. K.; Van Soest, P. J. *Forage fiber analyses (apparatus, reagents, procedures, and some applications)*; US Agricultural Research Service: 1970; No. 379.

(19) M'hiri, N.; Ghali, R.; Nasr, I. B.; Boudhrioua, N. Effect of different drying processes on functional properties of industrial lemon byproduct. *Process Saf Environ. Prot.* **2018**, *116*, 450−460.

(20) Pizzorno, J. E.; Murray, M. T. *Textbook of Natural Medicine-E-Book*; Elsevier Health Sciences: 2020.

(21) Petterson, D. S.; Choct, M.; Rayner, C. J.; Harris, D. J.; Blakeney, A. B. Methods for the analysis of premium livestock grains. *Aust. J. Agric. Res.* **1999**, *50* (5), 775−788.

(22) Ishikawa, M.; Warita, Y.; Takahisa, E.; Ohkubo, Y. Human-environment interactions (1): flavor and fragrance. *Comprehensive Natural Products II* **2020**, 595.

(23) Ameh, S. J.; Obodozie-Ofoegbu, O. Essential oils as flavors in carbonated cola and citrus soft drinks. In *Essential oils in food preservation, flavor and safety*; Academic Press: 2016; pp 111−121).

(24) Afzal, A.; Munir, A.; Ghafoor, A.; Alvarado, J. L. Development of hybrid solar distillation system for essential oil extraction. *Renew. Energy.* **2017**, *113*, 22−29.