THERMODYNAMIC ANALYSIS OF SOLAR ENERGY INTEGRATED MENTHA OIL DISTILLATION SYSTEM

THESIS

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for the degree of

DOCTOR OF PHILOSOPHY

IN

ENGINEERING

By

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DECLARATION

I hereby declare that thesis entitled "Thermodynamic Analysis of Solar Energy Integrated Mentha Oil Distillation System" submitted by me in fulfillment of the requirement for the degree of *Doctor of Philosophy* to Delhi Technological University (Formerly Delhi College of Engineering) is a record of *bona fide work* carried out by me under the supervision of Dr. Anil Kumar, Department of Mechanical Engineering, Delhi Technological University, Delhi.

I further declare that the work reported in this thesis has not been published and will not be submitted, either in part or in full, for the award of any other degree or diploma in any other Institute or University.

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CERTIFICATE

This is to certify that the work embodied in the *Thesis* entitled "Thermodynamic Analysis of Solar Energy Integrated Mentha Oil Distillation System" is a record of *bona fide research work* carried out by Mr. Ravi Kant (2K19/Ph.D/ME/08) in fulfillment of requirements for the award of degree of *Doctor of Philosophy* in Mechanical Engineering specialization in Thermal Engineering. He has worked under my guidance and supervision and has fulfilled the requirement which, to my knowledge, have reached the requisite standard for submitting the thesis.

The results in this thesis have not been submitted in part or full at any other University or Institute for the award of any degree or diploma.

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“गुरुर्ब्रह्मागुरुर्विष्णुर्गुरुर्देवोमहेश्वरः
गुरुः साक्षातपरब्रह्मातस्मैश्रीगुरवेनमः”

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RAVI KANT

ABSTRACT

Herbal medicines are used by most of the people around the world to address their health requirements. Therefore, medicinal and aromatic plants are essential since herbal medicines (essential oils) are made from their product. These oils are utilized in food as a flavoring agent, in cosmetic items as a scent, and in medicine for functional purposes. Various traditional and advanced extraction techniques are used for extraction of essential oil from aromatic and medicinal plants. Traditional methods are undesirable in terms of environmental perspective since they produce aerosols and greenhouse gases. These methods required high energy consumption and longer distillation extraction time, resulting in low efficiency and high cost. Therefore, solar energy assisted extraction is an advanced extraction method and an alternative approach to addressing the drawbacks of conventional oil extraction techniques because it is a never-ending source of clean energy.

In the present study, two different oil extraction systems (a) Conventional steam distillation (CSD) system (biomass based) (b) Solar steam distillation system (SSDS) have been analysed. Conventional steam distillation system has been analysed in terms of performance, energy balance, mass balance, environmental and economic assessment under different batch size of peppermint. Solar steam distillation system has been analysed based on energy, exergy, economic, exergoeconomic, environmental, and enviroeconomic point of view under different variable parameters such as solar radiation, relative humidity, ambient temperature and batch size of peppermint and eucalyptus. System is analysed for various batch sizes of two different medicinal plants (Peppermint and Eucalyptus) and compared. Moreover, the effect of lifespan of system on cost of essential oil per liter (CPL) and exergoeconomic parameters has been analysed in present study.

Performance of The CSD system was assessed in terms of thermal efficiency, productivity, essential oil yield, and extraction efficiency. Maximum hourly system productivity, cumulative productivity, maximum extraction efficiency, maximum essential oil yield and maximum hourly thermal efficiency were obtained for 1900 kg. The average increase in total productivity, extraction efficiency, and essential oil yield was 49.25%, 1%, and 26%, increasing in batch size from 1500 kg to 1900 kg. Process parameters of conventional distillation systems were optimized using RSM. Optimal process parameters are identified as 300 minutes of

extraction time and 1807.5 kg of batch size. The study explored the effect of peppermint batch sizes on energy measures, net CO_2 mitigation, and net carbon credit earned. Life cycle energy production factor (EPFs) and life cycle conversion efficiency (LCCE) for 18 years of life span were estimated to be 29.2, 33.1, 38.9, 12.6%, 14.8%, and 17.9% for 1500, 1700, and 1900 kg batch sizes, respectively. Maximum energy and fuel consumption were 4,966 MJ and 193 kg for 1500 kg, respectively. ROI, IRR and PBP were 73.9%, 85.7% and 1.26 years, respectively. The distillation system has a total embodied energy of 166,237 kWh. Lifetime CO_2 mitigation and net carbon credit earned are estimated to be 426.6, 438.5 and 568.8 tones and ₹1,95,239 (US$2,383.9), ₹2,63,049 (US$3,211.9) and ₹3,61,518 (US$4,414.3) for 1500, 1700, and 1900 kg batch size, respectively, if traded at the rate of 14.85 US$/ton.

The developed thermal model and characteristics equations have been used to analyse the solar steam distillation system. Optical losses in reflector as well as thermal losses in distillery, steam line, and condenser are calculated. Maximum and minimum system efficiency is calculated as 48.68% and 43.25 % for 2 kg of peppermint and 6 kg of eucalyptus, respectively, whereas highest and lowest exergy efficiency of system are 27.96 % and 22.50 % for 6 kg and 4 kg of eucalyptus leaves, respectively. Estimated return on investment (ROI), internal rate of return (IRR) and payback period (PBP) of SSDS producing 72 liters of peppermint oil per year were 14.03%, 18.77% and 5.67 years, respectively over the projected economic life span of 25 years. Cost per litre (CPL) values of produced peppermint oil at the same interest rate (5%) were 2.10, 1.89 and 1.75 US$/L for 20, 25, and 30 years of lifespan, respectively while for eucalyptus oil, the corresponding values were 2.53, 2.27 and 2.10 US$/L, respectively. Exergoeconomic parameter for peppermint oil is enhanced by 11.43 and 19.94% with increase in lifespan of system by 5 and 10 years, respectively at same interest rate of 5% while the corresponding values for eucalyptus oil are increased by 11.30 and 19.90%, respectively. CO_2 mitigated over the lifespan from SSDS for peppermint oil and eucalyptus oil based on energy approach is found as 2.37, 4.74, 7.11 tons CO_2 and 1.97, 3.95, 5.9 tons CO_2 for 2, 4 and 6 kg batch size, respectively. Whereas, the corresponding values based on exergy approach are 0.15, 0.11, 0.14 tons CO_2 and 0.12, 0.09, 0.12 tons CO_2, respectively. Thermal efficiency, EPF and LCCE of SSDS were reduced by 11.17, 16.8 and 17.76%, respectively for eucalyptus oil extraction than peppermint oil for constant batch size (i.e. 6 kg). Enviroeconomic parameter of SSDS for peppermint oil extraction is more than that of eucalyptus oil. This research will be helpful for

researchers and investors to find out various energy-saving potentials at different parts of system and to establish a cost-effective, environment-friendly solar distillation system for essential oil extraction from aromatic and medicinal plants.

The overall research work has undergone extensive analysis to produce responsible, system-effective results that are nourished by a detailed discussion of the results and conclusions, as well as future recommendations that may enlighten the researchers and inspire them to pursue additional potential developments in this field for the benefit of society, the environment, and the ecologically sustainable growth of peoples.

Keywords: Solar energy; Extraction; Distillation; Peppermint (Mentha); Eucalyptus; Productivity; Performance; Energy; Energy matrices; Exergy; Economic; Exergoeconomic; Environmental; Enviroeconomic analysis

NOMENCLATURE

A_s	Total Area of elliptical frame of Scheffler reflector (m^2)
A_o	Aperture area of Scheffler reflector (m^2)
C_c	Specific heat of calorimeter (kJ/kg-K)
C_w	Specific heat of water at constant pressure (kJ/kg-K)
C	Specific heat (J/kg^{o}C)
C_f	Specific heat of fibre (kJ/kg-K)
CV	Calorific value of fuel (KJ/kg)
E_b	Energy available at bottom of boiler (kWh)
$E_{cond,b}$	Energy available to generate the steam in boiler (kWh)
$E_{d,h}$	Energy required for distillation of herb(kWh)
E_{emb}	Embodied energy (kWh)
$E_{i,,}$	Energy available on Scheffler reflector (kWh)
$E_{l,c}$	Energy loss in condenser (kWh)
$E_{o,sl}$	Thermal energy available at steam outlet (kWh)
$E_{l,sl}$	Steam line losses (kWh)
$E_{cons,w}$	Energy consumed by water (kWh)
E_{out}	Thermal energy output (kWh)
$E_{x,i}$	Exergy at inlet to solar system (kWh)
$E_{x,o}$	Exergy at outlet of solar system (kWh)
h_{fg}	Latent heat of water (kJ/kg)
H	Enthalpy (J/kg)
I_g	Beam radiation (W/m^2)
L, L_v	Latent heat of vaporisation of water (kJ/kg)
m	Maas (kg)
M	Mass (kg/sec)
$\dot{m}_f$	Mass of fuel (kg/hr)
$\dot{m}$	Yield (kg/h)
m_w	Mass of water used in boiler of still (kg)
M_w	Moisture of herbs (wet basis)
m_{wc}	Mass of water in calorimeter (kg)
m_c	Mass of calorimeter (kg)

m_{s}, m_{v}	Mass of steam produced (kg)
m_{sc}	Mass of steam added in calorimeter (kg)
$\dot{m}_c$	Mass flow rate of cooling water (L/s)
n	No. of day of year
Nu	Nusselt number
P	Productivity of the system (L/h)
Q	Heat or energy (J/s)
R_m	Reflectivity of reflector (0.85)
Ra	Rayleigh number
t	Time (h)
T	Time (minutes), temperature (^oC)
T_s	Temperature of steam (^oC)
T_{1C}	Initial Temperature of water in calorimeter (^oC)
T_{2C}	Final Temperature of water in calorimeter (^oC)
$T_{i,c}$	Temperature inlet to condenser (^oC)
$T_{o,c}$	Temperature outlet to condenser (^oC)
V	Volume of oil (L)
X	Dryness fraction of steam

Subscripts

c	Condenser
cw	Cooling water
e	Extraction
eff	effective
f	Wood fuel
Hw	Hot water
i	In
L	Leaves
lost	Lost to environment
l	Loss
o	Out
oil	essential oil
s	System
sl	Steam line

s Steam, supplied

s,o mixture Steam oil mixture

SL Spent leaves

tank Extracting unit

uw Unused water

w Water

Superscripts

n number of years

Greek letters

ΔT Temperature difference (˚C)

η Efficiency

δ Solar declination angle (˚)

λ Receiver intercept factor

α Absorptivity of material

γ Factor of unhanding

Δ Change

τ Transitivity of material

θ Angle of incidence

ϵ Emissivity

₹ Indian National Rupee

Abbreviations

ACF Annul cash flow (US$)

AOC Annual operating cost (US$)

ANOVA Analysis of variance

CSD Conventional steam distillation

EOY Essential oil yield (%)

EO Essential oil

EPF Energy production factor

ET Extraction Time (Minutes)

LCCE Life cycle conversion efficiency (%)

OP Operational profit (US$)

PAT Profit after tax (US$)

PBP Payback period (Years)

PC Purchase cost (US$)

PO	Peppermint oil
ROI	Return on investment (%)
SD	Steam distillation
SSDS	Solar steam distillation system
SSR	Solid to solvent ratio
TAPC	Total annual production cost (US$)
TC	Total initial investment (US$)
TDC	Total direct cost (US$)
TEC	Total energy consumption
TIC	Total indirect cost (US$)
UP	Ultrasonic power

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INTRODUCTION

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INTRODUCTION

1.1 BACKGROUND

Good health is necessary for a decent quality of life. People from all over the world invest a lot of time and money in acquiring good health. Humans require an organized lifestyle and efficient treatment to preserve excellent health. The side effects of herbal medications made from medicinal and aromatic plants (MAP) are not as severe as those of allopathic medications [1]. Traditional herbal remedies have been employed in indigenous medications all across the world since the dawn of human civilization. The kind of herbal medicine that is most beneficial is essential oils (EOs). Mixture of volatile organic molecules that have been extracted from various MAP is known as EOs. They are the most efficient type of herbal medicine, and as a result, are widely utilized around the world. European Pharmacopeia 7th edition [2] defines essential oils as "aromatic products with a mixture of compounds derived from plant raw material, either separated by steam, dry distillation, or by a suitable mechanical technique without heating." Essential oil is separated from liquid phase without changing its chemical composition by physical method. Herbal plants are very important as most of the population depends on products of these plants (essential oils). The products of these plants are used in food, cosmetic items and medical field, etc. [3]. Various extraction techniques are used for essential oil (EO) extraction from several parts of medicinal plants such as barks, peels, leaves, buds, seeds, flowers, etc. [4]. Steam distillation [3], hydro-distillation [5], solvent extraction, supercritical fluid extraction [6], and subcritical extraction liquid [7] are some of the methods used to extract essential oils (EOs) from peppermint leaves as shown in Fig.1.1. Steam distillation (SD) or hydro-distillation (HD) is the most commonly utilized method [8]. In SD, thermal energy of the steam or water is used to evaporate the oil from the leaves and then the mixture of oil and water vapours is condensed in the condenser.

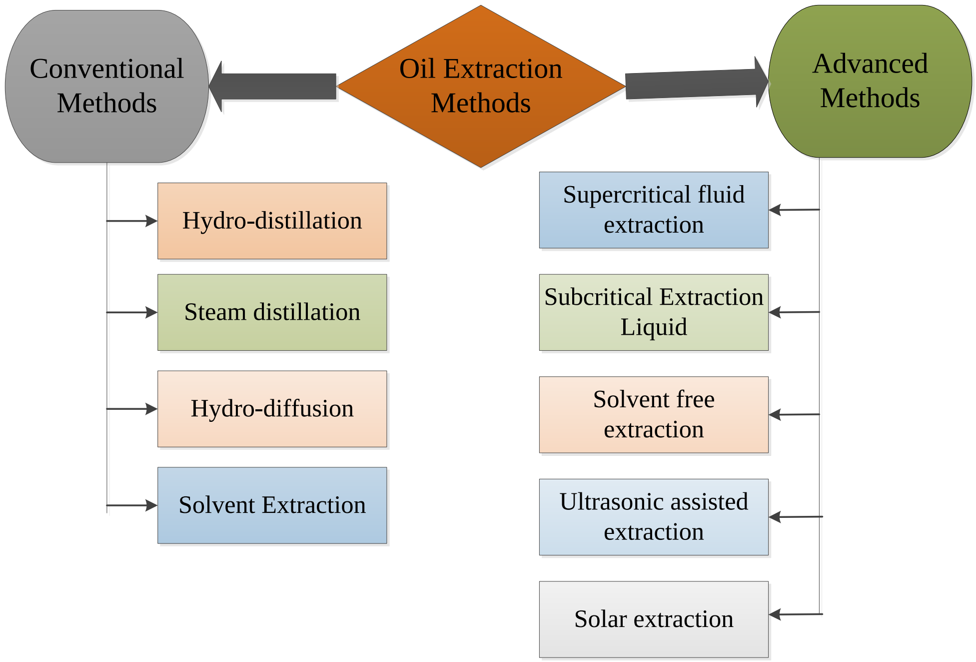


Fig.1.1 Oil extraction techniques [9]

Essential oils extracted from medicinal plants are also used for health benefits, as illustrated in Fig.1.2. Conventional SD technique extracts essential oil through water distillation by application of heat. Traditional methods of essential oil extraction are undesirable in terms of environmental perspective since they produce some aerosols and greenhouse gases. These methods required high energy consumption and longer distillation extraction time, resulting in low efficiency and high cost.

The world's energy demand depended heavily on fossil fuels over the past centuries. Energy consumption increases by an average of 1% and 5% annually in developed countries and developing countries, respectively [10]. Numerous predictions indicate that fossil fuels will not be able to supply this increasing demand and that their cost will rise significantly as a result of continuous increases in energy consumption. Renewable energy has attracted a lot of attention on a global scale in recent years due to the rising cost of fossil fuels as well as several environmental concerns including pollution, greenhouse effect, and global warming, etc. Renewable energy sources currently meet 14% of the world's energy demand, which is expected to increase in the future [11]. Solar energy reigns supreme among renewable energies. An average of 120 pet watts of solar energy is estimated to fall on the earth's surface each day. This shows that the amount of solar energy that the world receives in a day is equal to the amount of energy that will be needed in 20 years. According to data from the International Energy Agency, solar energy can meet roughly 45 percent of the world's energy needs by 2050 [12]. Solar energy has been used for various thermal processes, including pasteurisation, extraction, heating, and desalination [13]. Therefore, solar energy assisted extraction is an advanced extraction method and an alternative approach to addressing the drawbacks of conventional oil extraction techniques because it is a never-ending source of clean energy [13,14].

Fig.1.2 Applications of essential oils for health benefits

1.2 OIL EXTRACTION TECHNIQUES

1.2.1 Conventional methods

Traditional methods extract essential oil through water distillation by heating. Traditional methods are undesirable in terms of environmental perspective since they produce some aerosols and greenhouse gases. These methods required high energy consumption and longer extraction time, resulting in low efficiency and high cost.

a. Steam distillation method

Generally, SD technique is used for extracting oil from aromatic and medicinal plants. This technique extracted 93% of essential oils and other extraction methods were used to extract remaining 7% [15]. First step in steam distillation is cutting of fully grown aromatic plants. These plants are left in a field for several days for drying purposes. Plant 'hay' material is prepared by chopping of plants. Then a wagon is used to transfer 'hay' into distillery by creating a packed bed of leaves. There are four main types of equipment used in the steam distillation process: boiler, distillation unit, condenser, and florentine flask. Aromatic plants are brought into contact with steam generated in the boiler during distillation. As a result, essential oil components evaporate at temperature close to water and boiling point of oil components in the range of 250 to 350˚C. Steam and vapours of oil are condensed in condenser. Florentine flask was used to separate the oil from water [15,16]. Simple steam distillation technique is shown in Fig.1.3.

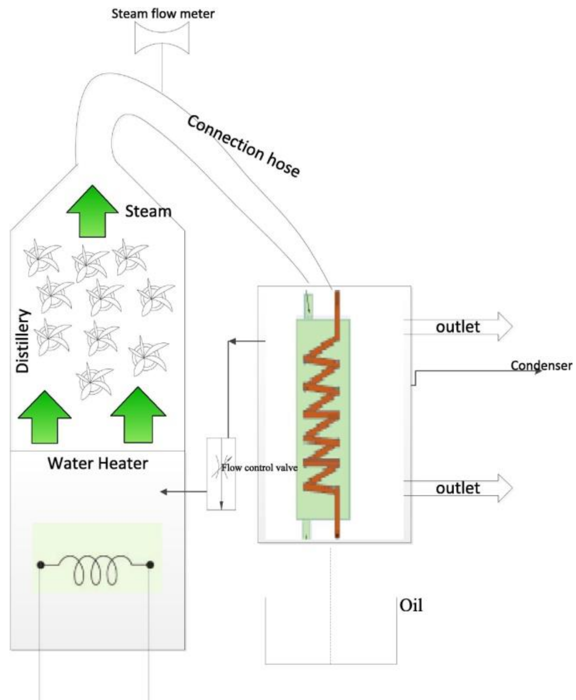


Fig.1.3 Steam distillation system [3]

b. Hydro-distillation (HD)

Avicenna discovered hydro-distillation, the oldest and simplest oil extraction technology, and was the first to establish alembic (vessel) extraction. The first plant that is used for extraction in this approach was risen. This method is mainly used for oil extraction from wood and flower material. Principle advantages of this technique are: (i) prevent the plant material from overheating, (ii) separation of the plant material under 100˚C [17]. Distillation is the process that generates steam in the boiler and then condenses it in condenser. Hydro-distillation (HD) technique is coupled with Clevenger apparatus. The main parts of Clevenger apparatus are round flask, separator and condenser. Plant material is poured into flask with water and heated up by the heat source. Plant material is mixed with water in flask to prevent adverse effect of heat. Essential oils evaporate due to heat and flow into the condenser. Oils and water are separated after condensation process [18]. Hydro distillation technique is illustrated in Fig.1.4. Ohmic assisted and microwave assisted HD are advanced HD technologies**.**

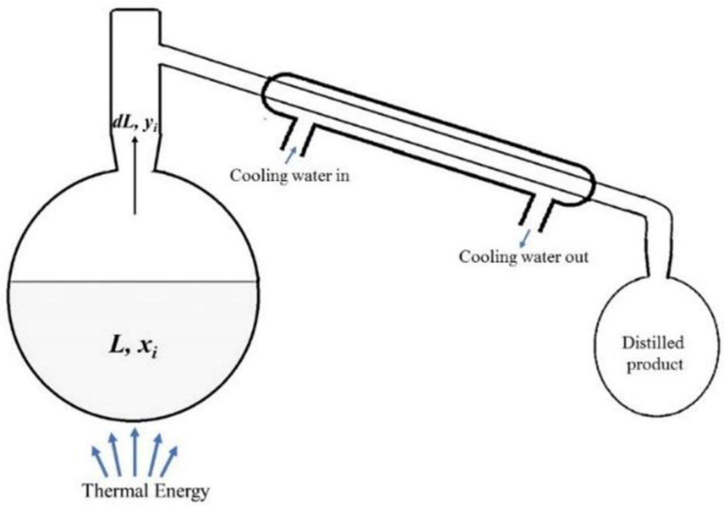


Fig.1.4 Hydro distillation method [18]

c. Hydro-diffusion

Hydro-diffusion process consists of a container to hold the plant material. Steam is supplied to heat the container. This method differs from SD in terms of steam supplied. In this method steam is supplied from the top of steam generator, whereas in steam distillation, steam is supplied from the bottom of generator. Only dried plant samples that can be destroyed at boiling temperatures are used in this approach. Plant materials are separated below 100˚C. Microwave steam diffusion (MSDF) is the advanced steam diffusion method [17]. Microwave hydro-diffusion method for oil extraction is shown in Fig. 1.5.

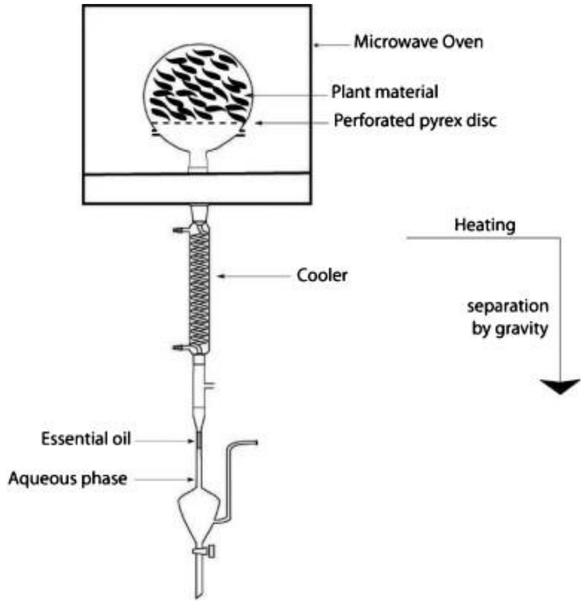


Fig.1.5 Microwave hydro-diffusion method [19]

d. Solvent Extraction method

This approach uses common solvents like petroleum, acetone, ether, methanol or ethanol, and hexane to extract fragile flower components that the application heat cannot separate**.** In this technique, solvents are mixed with plants sample and then mixture is moderately heated. Essential oils are extracted by filtration and evaporation of solvents. Resinoid, aroma and essential oil were found in the filtrate. Resinoid is mixed with alcohol to extract essential oil followed by distillation at low temperature. Alcohol absorbs aroma and evaporates when scented pure oil remains in the pan residue. This technique is more expensive and time-consuming than other techniques [20].

1.2.2 Advanced Extraction Methods

Conventional extraction methods have many disadvantages such as longer extraction time, lower efficiency, more organic solvent required, higher energy consumption, etc. Advanced extraction methods are alternative way to overcome the disadvantages of conventional extraction methods.

a. Solvent free microwave extraction (SFME)

The main components used in microwave extraction are round flask, condenser, and microwave. Dried leaves of herbs were placed in round flask and some solvents were added to the herbs. Prepared sample was placed in microwave oven for heating. Flask neck was connected to condenser and evaporated mixture of oil and water was condensed there. The volume of essential oils was determined by micropipette and anhydrous sodium sulphate was added to remove remaining water from oils. The microwave extraction process is shown in Fig.1.6. Long extraction time were observed at low microwave power and at higher power levels, dried leaves could burn [21].

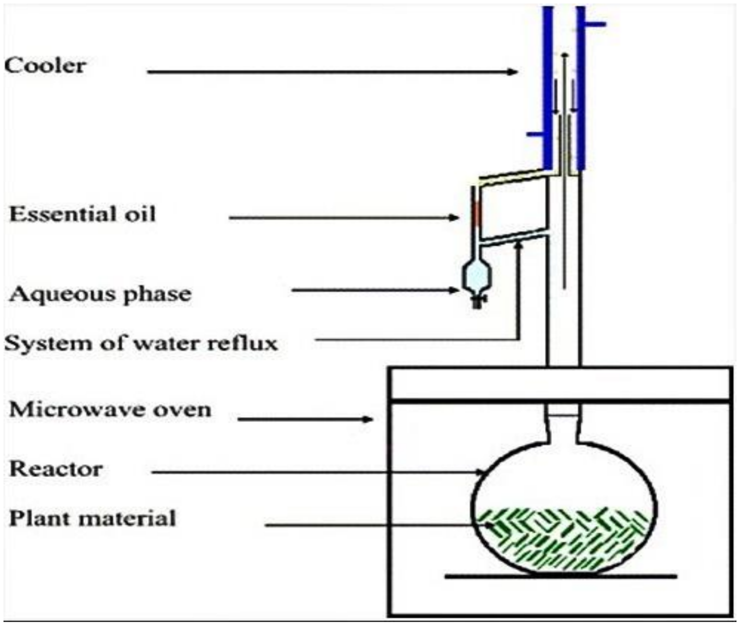


Fig.1.6 Microwave extraction technique [22]

b. Supercritical fluid extraction (SFE)

Critical temperature and pressure both are primary factors of supercritical fluid state. Fluids with these parameters show very attractive characteristics like higher diffusivity and density, low viscosity, etc. CO_2 is utilized as supercritical solvent for essential oil extraction. Fluid is recycled in repeated steps of compression or decompression in SFE process. The fluid is heated and compressed to achieve supercritical state of carbon dioxide. Thereafter, it passed through raw materials to feed volatile matter and plant compounds. Carbon dioxide and plant extracts mixture is sent into two separators to separate the plant extracts from CO_2 by decompression. Carbon dioxide, discharged from second separator, is circulated to storage tank. There are no solvents left in final products because carbon dioxide will eventually go back to gas under atmospheric conditions [23]. SFE technique of oil extraction is shown in Fig. 1.7.

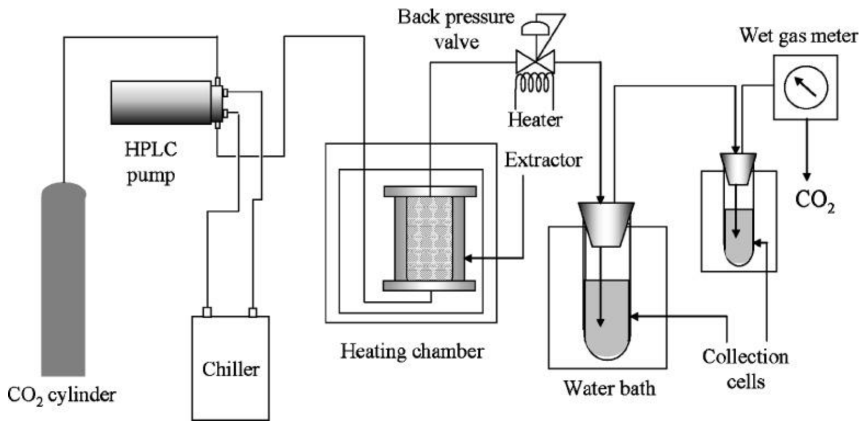


Fig.1.7 SFE technique [6]

c. Subcritical extraction liquid (SEL)

SEL technique uses water in the subcritical state for essential oil extraction. In the subcritical state of liquid, liquid pressure is greater than the critical pressure and less than the critical temperature or vice-versa. Water and carbon dioxide fluids are used for essential oil extraction in this technique. The extraction time is just 15 minutes in this approach, compared to 3 hours for traditional ways of extracting essential oils. Essential oils with more useful qualities, such as a higher proportion of oxygenated components and no detectable terpenes, can be extracted, resulting in significant cost savings in energy and plant materials [17,24].

d. Ultrasonic assisted extraction (UAE)

In the chemical and food industries, ultrasound has a major potential application. Ultrasound technology allows for quick extractions with excellent reproducibility and product purity, minimal solvent use, easy manipulation, and minimal set-up. Many matrices, primarily animal tissues, microalgae, yeasts, food, and plant materials, have been successfully used to extract, analyse, and synthesise many classes of food components, such as fragrances, pigments, antioxidants, and other chemical and mineral compounds. In order to enable mass transfer and the release of essential oils from plants, cavitation bubbles, produced during ultrasonication, generate micro-jets designed to destroy the glands that contain the oils. The operating parameters, such as temperature, treatment time, ultrasound frequency and intensity are important for the efficient design and operation of sono-reactors as they have a significant impact on the cavitation effect. Literature reports that the essential oils produced using ultrasound-assisted extraction revealed less thermal deterioration, excellent quality, and good flavour and fragrance with higher productivity [25,26]. Schematic of ultrasonic extraction of essential oil from medicinal plants is shown in Fig.1.8.

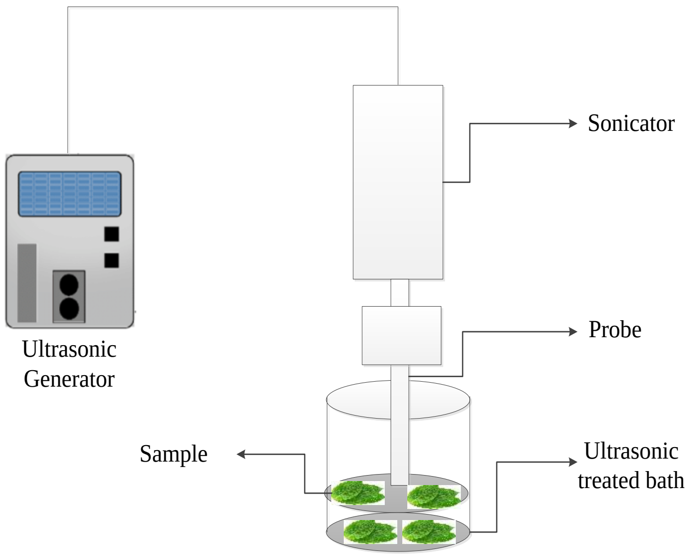


Fig.1.8 Ultrasonic assisted extraction

e. Solar assisted extraction

Solar distillation system mainly consists of four parts named Scheffler reflector, boiler, distillation unit, condenser, and Florentine flask. Solar radiation falls on reflector and is reflected to boiler. Boiler water gets heated up by solar radiation and converted into steam. Boiler is connected to extraction unit, which is filled up with peppermint plants. Peppermint plants are loaded in extraction unit at the two mesh grid frames that are located at bottom and middle of distillery. The steam passes through peppermint leaves and oil evaporates from this steam. Extraction unit is connected to condenser using a connection hose and mixture of steam and oil is condensed in the condenser. Oil and water are separated in Florentine flask due to density difference. Oil remains at the top as water density is higher than oil. Schematic of SSDS is shown in Fig.1.9

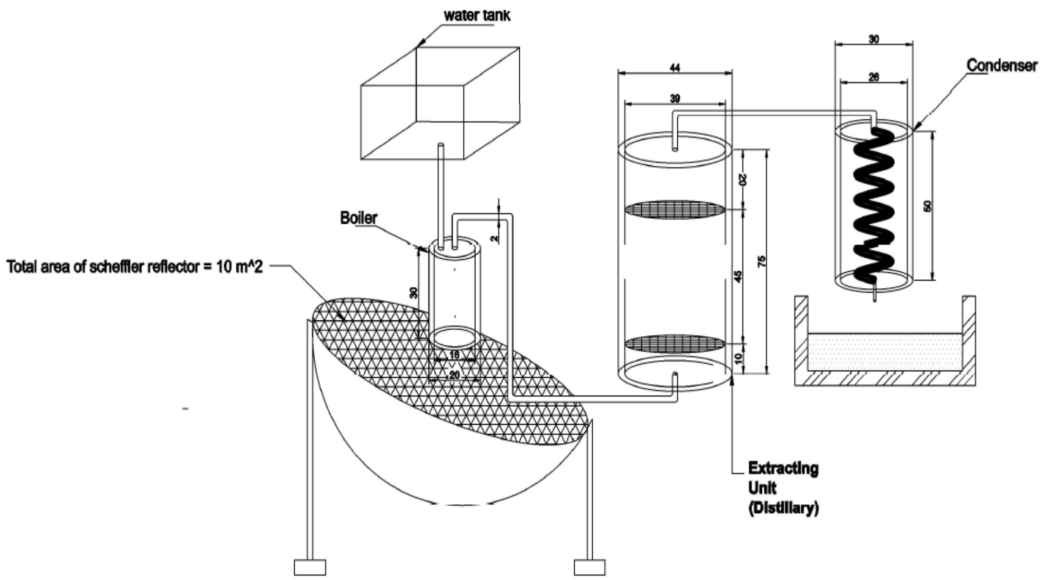


Fig.1.9 Solar assisted extraction system

1.3 ORGANIZATION OF THESIS

The overall *Thesis* entitled **"Thermodynamic analysis of solar energy integrated mentha oil distillation system"** is prepared in five chapters comprising, introduction, literature survey, methodology (i.e., a sequential follow-up and thermal modelling for solar energy integrated mentha oil distillation system), results and discussion, conclusions and recommendations for future work followed by the appendixes, references, list of publications, and curriculum vitae. Further, the schemes of the entire chapters are represented as follows

Chapter 1 reflects realistic background of extracts from aromatic and medicinal plants useful for human beings, and its application. It defined generalised introduction towards solar assisted extraction techniques of essential oil with a motivation related to necessity of essential oils. This chapter offers a better solution for extraction of essential oil from aromatic and medicinal plants. Further, types of oil extraction techniques for extraction of essential oil from aromatic and medicinal plants, and working principle have been discussed.

Chapter 2 establishes a vital stage of solar distillation technology for oil extraction from aromatic and medicinal plants (historical background to latest developments) along with a brief glimpse of different extraction methods (Conventional and Advanced extraction methods) for essential oil through the literature survey. Further, historical background is classified in terms of technological advancement in oil extraction methods, thermal modelling, economic analysis and environmental assessment, essential oil market, and GC-MS analysis of essential oil. In this chapter, the problem statement has been identified with the proposed research gap and targeted objectives for the present research work that has been carried out at the *Delhi Technological University (DTU), Delhi*. Also, the research scope and research contribution to society have been presented in this chapter to justify the goodness of this technology towards society and thus the nation.

Chapter 3 sets the analytical methodology with sequential steps to achieve the research objectives as mentioned in chapter two. The exploration of conventional and solar distillation system for peppermint oil extraction with its detailed assumptions, analytical parameters, system description, and specifications have been done that are utilized while developing thermal model of the proposed systems. Then the detailed thermal model and characteristic equations along with the respective performance parametric observations are given in terms of mathematical expressions under the meteorological conditions of Jhansi (U.P) for conventional system and New Delhi for solar distillation system for a clear archetypal day in the winter season of the month November.

Chapter 4 contains the results and discussion for both the proposed systems (Conventional and Solar distillation system) that comprise the evaluation of yield, thermal performance, operational performance, energy and exergy analysis, economic analyses and the evaluation of pollutants emission-mitigations, and environmental cost (i.e., carbon credit values in the international market) of the proposed systems. Process parameters of conventional distillation systems are optimized using response surface methodology (RSM). Further, a comparative study is being presented for both the proposed systems with the previous research based on the similar parameters of different systems.

Chapter 5 represents the conclusion of the entire observations made for both the proposed systems in this Thesis. Further, all of the observations have been concluded with suggestions for future research that would encourage the researchers to continue looking into possible improvements in this area for the benefit of the environment and society.

The next chapter establishes a vital stage of solar distillation technology for oil extraction from aromatic and medicinal plants (historical background to latest developments) along with a brief glimpse of different extraction methods (conventional and advanced extraction methods) for essential oil through the literature survey. Further, historical background is classified in terms of technological advancement in oil extraction methods, thermal modeling, economic analysis and environmental assessment, essential oil market, and GC-MS analysis of essential oil. In this chapter, the problem statement has been identified with the proposed research gap and targeted objectives for the present research work that has been carried out at the Delhi Technological University (DTU), Delhi. Also, the research scope and research contribution to society have been presented in this chapter to justify the goodness of this technology towards society and thus the nation.

CHAPTER: 2

LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

It is widely known that people have been extracting essential oils from aromatic and medicinal plants since the beginning of human civilization, however many of their original functions have been lost to time. The essential oils have been used for various applications from ancient time and are regarded with great fascination. In addition to using them in the production of fragrances and cosmetics, they have also been employed for medicinal purposes, which have gradually replaced their initial usage as a tool for enhancing the taste and flavour of food. Ancient Egyptians employed essential oils in medicine, cosmetics, and the art of preparing bodies for tomb through preservation. The Vedas categorised the use of essential oil for treatment and worship throughout Asian continent. Furthermore, essential oils have been used by humans throughout history for a variety of objectives, such as religious rituals, perfumery, and the treatment of fatal diseases [27]. Conventional and Solar distillation system for essential oil extraction may play a very important role in this field, as depicted in the following literature survey.

2.1.1 Technological advancement in extraction methods

This section covers technological advancement in essential oil extraction methods from aromatic and medicinal plants. Various extraction methods such as SD, HD, SFE, SEL, UAE, SFME and solar assisted extraction are used for essential oil extraction from aromatic and medicinal plants. Various studies have been conducted on performance of extraction methods for essential oil extraction from peppermint.

Afzal et al. developed a hybrid solar steam distillation system (HSSDS) for extracting EO from peppermint and eucalyptus plants and calculated essential oil yield (EOY). A secondary biomass system is combined with a distillation system to meet energy demand at night and in adverse weather conditions. Yields of 0.40% and 0.59% w/w were obtained from peppermint and eucalyptus, respectively [28]. Radwan et al. developed SSDS to extract oil from lavender plant and determine system performance. The effect of boiler water inlet flow rate and batch size on performance parameters was analysed in this study. The optimum condition of the system was obtained as 800g batch size and 1.25 l/h boiler inlet water flow rate (BIWFR) [15]. Munir et al. used SSDS for extracting the oil from different plant material. In this study, various components of solar distillation system are designed with a clear mathematical description. Efficiency of system and energy used for 10kg batch were obtained as 33.21% and 3.5 kWh, respectively [29]. In another study, Radwan et al. analyzed the effect of batch size (300, 500 and 700 g) and BIWFRs (1.00, 1.25 and 1.50 l/h) on the performance parameters of electrical steam distillation system. Performance parameters were considered as essential oil yield, productivity, extraction efficiency and energy consumption. Results showed that system performance increased with an increase in BIWFR and batch size of peppermint. Highest performance was obtained at 700 g batch size and 1.5 l/h BIWFR [30]. Gavahian and Chu extracted the EO from lavender by ohmic accelerated steam distillation method (OASDM). The extraction parameters of OASDM were compared with those of a steam distillation (SD) system. Results showed that OASDM is time-saving and energy-saving technology as compared to SD. This method reduces the extraction time and energy consumption by 55% and 58%, respectively, for the same quantity of raw material [31]. Kulturel and Tarhan used a SSDS for essential oil extraction from Mentha peperita L. and Mentha spicata L. Seven parabolic collectors were connected in series for heating the heat transfer fluid (oil). System performance was evaluated in this study. A batch size of 5 kg mint plants was used per day and 26 to 40 ml of oils were extracted from the system [32]. Cassel et al. extracted the essential oil from rosemary, basil and lavender plants by SD system. A mathematical model was developed to validate the experimental results in this study. The maximum EOY obtained for lavender, rosemary and basil was 0.32%.0.51% and 0.38% (w/w), respectively [33]. Ohmic assisted and microwave assisted HD methods are advanced HD technologies. Gavahian and Farahnaky demonstrated an ohmic assisted hydro-distillation method (OAHDM) for extracting oil from ethanol and other medicinal plants. Performance of the system was compared with conventional distillation method. Results concluded that processing time and energy consumption were lower for OAHDM than for conventional distillation [18]. Dao et al. extracted EOs from lemon by hydro-distillation technique. Results indicated that an optimum yield of 3.9 % (w/v) was obtained at a heating power of 204 W, a water-material ratio of 3:1 ml/g, and a processing time of 60 min [34]. Memarzadeh et al. extracted EOs from bhaktiary savory leaves by two methods: conventional hydro-distillation (CHD) and microwave assisted steam distillation (MASD). The effects of two extraction methods described above on the quality, quantity and extraction time were investigated in this study. MASD method was superior to the CHD method in terms of time and energy saving, less waste water, and oil quality, etc. [5]. Hamid et al. used hydro- distillation method for extracting the cypress oil. This study investigated the effects of process variables (temperature, solvent to solid ratio and extraction time) on the oil yield. Maximum oil yield was obtained at a processing time of 4 h, a solvent to solid ratio 10 ml/g, and a temperature of 100˚C [35]. Sadeh et al. extracted the essential oil from rosemary plant by hydro-distillation and solvent extraction method and investigated the effects of season, genotype and extraction technique on oil composition and oil yield [36]. Dao et al. used hydro-distillation to distillate the oil from pomelo peel [37]. Taban et al. used four different hydro-distillation methods: hydro-distillation (HD), ohmic-assisted hydro-distillation (OAHDM), microwave-assisted hydro-distillation (MAHD), and hydro-steam distillation (HSD), to distillate oil from sweet bay plant. All four techniques described above calculated the oil yield for the same amount of sweet bay. MAHD and OAHDM are the faster and cleaner techniques due to their short processing time and lower energy requirement [38]. Drnic et al. distillate the essential oils from O. vulgare L. subsp.hirtum by HD and MAHD techniques. Performance of MAHD techniques was compared with HD technique. Results shown that MAHD technique was superior to HD method in terms of total process time, oil yield and environmental impact [39,40].Aziz et al. extracted the essential oil from orange peel and investigated the separation period for MSDF and steam diffusion (SDF). Extraction time for MSDF was 12 min as compared to SDF method, which was 40 min [17]. Ouariachi et al. used solvent extraction technique to extract oils from Ptychotisverticillata plants and investigated the antioxidant activity of the plant. Results found that oil contains 48% phenolic compounds and carvacrol (44.6%) and thymol (3.4%) are the key compounds [41]. Ozen et al. extracted the essential oil from Thymus praecox subsp. skorpilii var. skorpilii (TPS) by solvent extraction technique and examined its antioxidant activity and chemical composition by mixing the sample with various solvents such as water, ethanol and methanol [42]. Cordoso-Ugarte et al. designed microwave assisted extraction (MAE) for extracting essential oil from basil and epazote plants. Results indicated that essential oil yields were affected by power, solvent quantity and heating time. MAE technique was compared with steam distillation in terms of yield, physical and chemical properties [21]. Lucchesi et al. used solvent free microwave extraction (SFME) to extract oils from aromatic plants of basil, garden mint and thyme and compared it with the CHD technique. Results concluded that SFME was superior to CHD in terms of cost, processing time and energy consumption [22,43]. Bayramoglu et al. applied SFME for extracting the oils from origanum vulgare L. and investigated the effects of extraction time and microwave power on the essential oil yield. Higher oil yield was obtained from SFME as compared to CHD. Results showed that extraction time of SFME was reduced by up to 80% at the microwave power of 622 W compared to that of CHD [44]. Delazar et al. presented an overview of microwave extraction techniques for extracting oil from aromatic plants [45]. Sodeifian et al. applied SFE technique to extract essential oil from Cleome coluteoides Boiss aerial parts and optimized the process parameters of SFE by using response surface methodology [46]. Kouchaksaraie and Niazmand used Supercritical CO_2 extraction technique to extract antioxidant compounds from Crocus sativus petals [47]. In another study, Bogdanovic et al. analyzed the yield and chemical composition of lemon balm obtained by two-step CO_2 extraction at high pressure [48]. Reverchon presented an overview of analytical, modeling and processing perspectives of SFE technique. This study analyzed the suitability data on pure constituents of EO and discussed the processes suggested for isolating and fractioning the EOs by supercritical CO_2, as well as the corresponding modeling features [49]. In another study, Sodeifian and Sajadian extracted EOs from Echinophora platyloba DC using SFE technique [50]. Kubatova et al. used SEL technique to extract lactones from kava root and compared it with soxhlet water extraction technology. In subcritical water extraction technique, an extraction time of 2 h was required for complete extraction at 100˚C, while an extraction time of 20 min was enough at 175˚C. Soxhlet extraction technique requires extraction time of as long as 6 h for essential oil extraction and reduces the yield by 40-60% compared to subcritical water technique [7].

SD, Hydro-distillation and microwave assisted extraction techniques for essential oil extraction from different aromatic and medicinal plant are depicted in Table.2.1, Table 2.2 and Table 2.3, respectively. Performance affecting parameters of essential production by various extraction methods from aromatic and medicinal herbs are illustrated in Table 2.4.

Table 2.1 SD systems for extracting oil from medicinal plants

Medicinal Plants	Heat Source	Outcomes	References
Eucalyptus and Peppermint	Solar disc	• HSSDS was used for EO extraction from eucalyptus and peppermint. • Essential oil yield was evaluated as 0.40% and 0.59% w/w from peppermint and eucalyptus.	[28]
Rosemary, cumin, cloves, Peppermint	Scheffler reflector	• SSDS was developed for extracting EOs from different medicinal plants. • System efficiency and energy required to process a batch size of 10 kg were evaluated as 33.21% and 3.5 kWh, respectively	[29]
Lavender	Solar disc	• SSDS was used for essential oil extraction from lavender and system's performance was evaluated. • Results indicated that boiler water inlet flow rate and batch size of lavender affect the performance parameter. • Optimum conditions were achieved at 1.25 l/h BIWFR and 800 g batch size.	[15]
Peppermint	Electric heater	• In this study, performance of steam distillation system was evaluated. • System's Performance was affected by BIWFRs (1.00, 1.25, 1.50 l/h) and batch size of peppermint (300, 500, 700 g). • The optimum batch size of peppermint and BIWFR was obtained as 700g and 1.50 l/h, respectively.	[16]

Lavender	Electrical electrodes	• OASDM system was developed to extract oil from lavender. • The processing time and energy consumption in OASDM technology were reduced to 55% and 58% compared to SD technique.	[31]
Mentha peperita L., Mentha spicada L.,	Parabolic collectors	• Seven collectors were connected in series to meet energy demand. • 26 to 40 ml of distilled oil was obtained from 5 kg plant material.	[32]
Rosemary, basil, lavender	Electric resistance	• In this study essential oils were distilled from various plant materials by electric steam distillation. • A mathematical model was formulated to validate the experimental results.	[33]

Table 2.2 Hydro-distillation techniques to distillate the oil from different herbal plants

Herbal Plants	Heat Source	Outcomes	References
Ethanol and various plants	electrical	• Performance of OAHDM technique was compared with conventional distillation method of oil extraction. • OAHDM extraction technique was superior to conventional technique in terms of time, energy saving, and operational cost.	[18]
Fresh lemon	electrical	• Present study investigated	[37]

		the effects of process parameters on oil yield. • Maximum yield was achieved at a power of 204 W, a water-material ratio of 3:1 ml/g, and a processing time of 60 min.	
Bhaktiary savory	Electrical and microwave	• CHD and MASD techniques were used for the distillation of bhaktiary savory plant. • Performance parameters of MASD such as energy consumption, reaction time and environmental impact were lower than those of CHD.	[5]
Cypress	electrical	• HD technique was used to distillate the EOs from cypress plant. • This study investigated the effect of process parameters such as process time, solvent-solid ratio and temperature on the oil yield. • Optimum oil yield was obtained at a solvent- liquid ratio of 10:1 ml/g, process time of 4 h, and a temperature of 100˚C.	[35]

Rosemary	electrical	• Hydro-distillation and solvent extraction technique was used to distillate rosemary essential oil. • Present study investigated the effects of season, genotype and extraction technique on oil composition and oil yield	[36]
Sweet bay	Conventional, electrical, microwave	• This study aims to compare the performance of four hydro distillation techniques, HD, OAHDM, MAHD and HSD, used to distillate sweet bay oil. • Current study examined the essential oil yield, anti-oxidant activity and chemical composition. • EOYs obtained by above described methods were 1.40, 0.83, 1.00 and 0.74 (% w/w), respectively	[38]
O. vulgare L. subsp.hirtum, Rosemary	Microwave	• This study calculated total extraction time, essential oil yield, and CO_2 emissions for HD and MAHD technology. • MAHD techniques operated at various microwave power of 180, 360, and 600 W. • Results concluded that total	[39,40]

	extraction time was less for MAHD technique when the microwave was operated at 600 W microwave power. • Maximum essential oil yield of 7.10% was obtained for MAHD technique when the microwave was operated at 600 W microwave power and was 5.81 % for HD technique.	

Table 2.3 Remarks and findings of microwave extraction technologies

Aromatic plants	Outcomes	References
Basil and epazote	• Process parameters of MAE method were compared with those of SS method in present study. • EOY was affected by heating time, microwave power and solvent quantity. • MAE technique had lower cost, energy consumption, processing time and CO_2 emissions than other extraction technologies.	[21]
Basil, garden mint and thyme	• SFME was developed to extract the oil from garden mint, thyme and basil and compared it with CHD technique. • SFME was a green extraction method and superior to CHD method in terms of costs, energy and time saving and environmental	[22]

	pollution.	
Rosemary plants	• EOs are extracted from rosemary plants by SFME method. • SFME method requires less extraction time and energy consumed compared to CHD method.	[43]
Origanum vulgare L.	• SFME technique was used to extract the oils from oregano and compared it with CHD method. • This study investigated the effects of extraction time and microwave power on oil yield. • The essential oil yield obtained for SFME and CHD techniques was 0.054 ml/g and 0.048 ml/g, respectively. • Results indicated that extraction time was reduced by up to 80% at the microwave power of 622 W compared to CHD.	[44]

Table 2.4 Performance affecting parameters of essential oil production

Extraction Method	Aromatic Plants	Operating Parameters	Outcomes	References
SD	Lavender	Batch size (g) 400, 600 and 800 Boiler inlet flow rate (l/h) 1.00, 1.25 and 1.50	• Maximum system productivity, EOY and extraction efficiency, and system efficiency were obtained as 7.3 ml, 0.785%, 98.13% and 60.25%, respectively for 800g batch size and 1.50 l/h BIFR of	[15]

			water. • Extraction time required for 400, 600 and 800g batch size was 120, 240 and 240 minutes, respectively.	
	Peppermint	Batch size (g) 300, 500 and 700 Boiler inlet flow rate (l/h) 1.00, 1.25 and 1.50	Maximum system productivity, EOY and extraction efficiency, and system efficiency were obtained as 6.2 ml, 0.797%, 88.57% and 60.25%, respectively, for 700g batch size and 1.50 l/h BIFR of water.	[16]
	Melissa, Peppermint, rosemary, cumin, and cloves	Batch size (kg) 11.6, 9.1, 3.0, 1.2 and 0.8	Essential oil content for Melissa, Peppermint, rosemary, cumin, and cloves was obtained as 1.425, 28.2, 4.6, 12.4 and 44 ml, respectively.	[29]
	Eucalyptus Peppermint Pinus	Batch size (kg) 10	EOY for pinus, peppermint and eucalyptus was calculated as 0.31%, 0.40% and 0.59%, respectively.	[28]
HD MAHD	O. vulgare L. ssp. Hirtum	_____ Microwave Power (W) 600, 300, and 180	• EOY for MAHD at 600, 360, and 180 W was 7.10, 5.67, and 2.55%, respectively, while it was 5.81% for HD. • The highest and lowest EOY	[39]

			was obtained for MAHD at 600W and 180 W, respectively.	
Supercritical CO_2 - extraction	Cleome coluteoides Boiss aerial parts	Pressure (bar) 100-220 Temperature (K) 308-328 Particle Size (mm) 0.3-0.9 Extraction time (min) 30-150	Maximum oil yield was obtained as 0.658 at optimum operating parameters of 220 bar pressure, 308K temperature, 0.58 mm particle size and 135 min extraction time.	[46]
HD MSHD	Bakhtiari savory	Extraction time (min) 60, 90 and 150 10, 20 and 75	Maximum oil yield of 1.8±0.012 ml/kg at optimum extraction time of 20 and 150 min for MSHD and HD.	[5]
SWE SOX	Kava root	Temperature (ºC) 100 and 175	Extraction time required for essential oil using SWE was 120 and 20 min at 100 and 175 ˚C, respectively.	[7]
MAE	Basil and	Microwave power	Maximum EOY for basil and	[21]

	Epazote	(W) 70 and 80 Extraction time (min) 20 and 30 Amount of water (mL) 400 and 500	epazote was obtained as 0.47% and 0.39%, respectively under a power of 80 W, an extraction time of 30 min, and an amount of water of 500 mL.	
SFE	rose geranium	Extraction time (min) 5, 15, 30, 60 and 180 Temperature (°C) 40, 80, and 100 Pressure (bar) 80 and 160	Maximum yield of 0.2% was calculated at pressure of 90-100 bars, temperature of 40˚C and extraction time of 15-30 minutes.	[51]
UAHD	Cinnamom m cassia bark	Ultrasound time (min) 10, 20, 30, 40, 50 and 60 Ultrasound Power	Maximum EOY of 2% was obtained at ultrasound time of 30 min, ultrasound Power of 300 W, extraction time of 60 min and liquid solid ratio of 6 ml/g.	[52]

	(W) 100, 200, 300, 400 and 500 Extraction Time (min) 15, 30, 60, 90 and 120 Liquid-solid ratio (ml/g) 4, 6, 8, 10 and 12		
Medicinal Plants	Ultrasonic Power (W) 70, 110, 150, 190, 210, 230 and 250 Extraction temperature (˚C) 25, 30, 35, 40, 45, 50, 55 and 60 Extraction time (min) 5 to 20	Maximum oil yield was achieved as 55.44 ± 0.53 under optimal condition of 20 min extraction time, 40˚C extraction temperature and 210 W ultrasonic power.	[26]

2.1.2 Thermal modeling

Thermal modelling is a method of determining the efficiency of any thermal system in order to conduct theoretical study. Thermal model has been developed for solar distillation system depending on energy and exergy balance of its different parts. These models are beneficial for system design pre-manufacturing and time saving [53].

Ezzarrouqy et al. performed energetic and exergetic analysis of solar steam distillation system of rosemary leaves. Exergy and optical efficiencies obtained up to 26.62% and 50.97%, respectively, with average intensity radiation of 849.1W/m2 and 6 kg of rosemary leaves during 4 hours distillation [13]. Madadi et al. performed energy and exargy analysis for parabolic dish collector. Heat transfer between sun and receivers is the source of the most exergy destruction, accounting for 35 % to 60 % of total exergy destruction [54]. Maharaj and McGaw developed a mathematical model for solar steam distillation system for extraction of basil leaves and a small scale pilot plant was used for testing. The model shows that oil components will be removed from the plant matrix and transferred to the steam [55]. Miladi et al. investigated energy performance of vacuum membrane distillation powered by solar energy, which is coupled with a liquid ring vacuum pump using several energy assessment criteria. The average energy efficiency and energy consumption were between 56.2-59.3% and 671 and 699 kWh/m3 [56]. Munir and Hensel designed a SSDS for extraction of oil and determined efficiency and average power of system as 33.21% and 1.548 kW, respectively [14]. Wei et al. presented an exergy and exergoeconomic evaluation to find possible energy reductions in distillation processes. The findings show that the exergy-savings potential provides comparisons of energy-savings potentials among various system components, while the cost-savings potential value highlights the cost that may be avoided in today's technology and economic context [57]. A five-column methanol distillation method was studied by Sun et al. for energy and exergy. Energy consumption and the overall exergy loss of the five column system can be reduced by 15.23 % and 21.5 %, respectively, as compared to four column system [58]. Cui et al. presented energy, exergy, and economic assessments of commercial styrene distillation schemes, which use traditional distillation columns to purify styrene. The separation of ethylbenzene/styrene accounts for around 65% of the overall energy requirement [59].

2.1.3 Economic and environmental assessment

Economic assessment of conventional and advanced extraction techniques for essential oil from medicinal and aromatic plants can be performed by determining the production cost or Cost of manufacturing (COM) of essential oil extraction from medicinal and aromatic plants. COM includes fixed initial investment cost (FCI), labour cost (LC), raw material cost (RMC), waste treatment cost (WTC) and utility cost (UC). The environmental impact of various extraction techniques is assessed by calculating energy requirements and carbon dioxide (CO_2) emissions Various studies have been performed on economic analysis and environmental impact of essential oil extraction methods.

Ma'azu et al. extracted EO from eucalyptus citriodora plant leave by SD method and performed economic analysis. Results concluded that the cost of oil produced by SD method was estimated at 15.85 US$/ litre. Internal rate of return, return of investment and payback period of SD method was calculated as 29.64%, 125%, and 0.75 years [60]. In another study, economic analysis of EOs extracted from rosemary, anise and fennel by SFE method was done and compared with SD method. Results showed that manufacturing cost of rosemary, anise and fennel EO in SFE technique was estimated at 42.69, 21.21, and 10.93 US$/kg, respectively, whereas in SD method, manufacturing cost was 76.50, 51.31, and 24.40 US$/kg, respectively [61]. Moncada et al. used three extraction techniques (water distillation, solvent extraction and SFE) to extract essential oil from rosemary and oregano. This work used techno-economic analysis and environmental assessment for these extraction techniques. Results showed that lowest production cost (6.71 US$/kg) was obtained for oregano oil using SFE with full energy integration, while for rosemary, production cost (6.75 US$/kg) was lowest for water distillation technique with full energy integration. Hexane based solvent extraction is the most hazardous technique in terms of environmental perspective. At the same time, water distillation without any energy integration is the most harmful technique in terms of carbon impact. The most effective technique for rosemary oil is water distillation with full energy integration, while the best method for oregano oil is SFE from a technological, economic, and environmental point of view. [62]. In another study, Moncada et al. performed techno-economic and environmental assessments of oil extraction from lemon grass and citronella using hydro distillation, supercritical fluid extraction and solvent extraction. Minimum cost of production and minimum carbon (CO_2) emission for lemon grass and citronella was obtained as 7.50US$/kg and

6.48US$/kg, and 0.73 kg/kg oil and 0.79 kg/kg oil, respectively, using hydro distillation with full energy integration [63]. Production cost and CO_2 emissions of different EO obtained by various technologies are given in Table 2.5.

Table 2.5 Production cost and CO_2 emissions for different EO extraction techniques

S. No.	Extraction method	Essential oil	Cost (US$/kg)	CO_2 Emission (kg/kg oil)	Reference
1	Steam distillation (SD)	Eucalyptus citriodora	15.85	__	[60]
2	Supercritical fluid extraction (SFE)	Rosemary	42.69	__	[61]
		Anise	21.21	__	
		Fennel	10.93	__	
	Steam distillation (SD)	Rosemary	76.50	__	
		Anise	51.31	__	
		Fennel	24.40	__	
3	SFE	Oregano	6.71	0.73	[62]
	Solvent extraction		8.35	1.05	
	Water distillation		7.05	0.80	
	SFE	Rosemary	7.45	0.68	
	Solvent extraction		8.53	1.04	
	Water distillation		8.64	0.78	

4	HD	Lemon grass	7.50	0.73	[63]
	SFE		7.68	0.75	
	Solvent extraction		8.57	1.04	
	HD	Citronella	6.48	0.79	
	SFE		6.88	0.80	
	Solvent extraction		9.50	1.13	
5	HD	O. vulgare L. spp.hirtum	__	0.187	[39]
	MAHD				
	600 W		__	0.0270	
	360 W		__	0.0246	
	180W		__	0.0424	
6	HD	Bakhtiari savory	__	3.60	[5]
	MSHD		__	0.216	

2.1.4 Essential oil market

Global production of the 20 most popular essential oils is estimated to exceed 104,000 tonnes. This figure is used as a reference because the figure includes the cosmetic industry and the food, medical, and household sectors. Also, apart from these 20, there are many types of minor oils, such as caraway oil, cumin oil, valerian oil, etc. Drink and beverage industry is a part of the food industry. Western Europe accounts for a significant share of the worldwide cosmetics and toiletry market, accounting for over 31%, followed by North America and Asia Pacific.

Large multinational corporations also dominate pharmaceutical industry. North America, European Union (EU), and Japan are the three largest markets in pharmaceutical sector [64].

USA, China, Brazil, Mexico, Morocco, Indonesia, India, and Egypt are the main producers of EOs. Percentage share in production of essential oils of these countries is 24%, 20%, 8%, 5%, 5%, 4% and 2%, respectively. It is estimated that developing countries produce 65% of global production. USA (40%), Western Europe (30%) and Japan (7%) are the main consumers of EOs. USA, UK, France, Japan and Germany are the main countries that import the EOs. USA, France, India, UK and Brazil are the main exporter of EOs. The USA is the largest importer and exporter of EOs, accounting for 14% (US$390.9 m) of global imports and 17% (US$351.7 m) of global exports.

India produces 4% of world production of EOs and only 0.4 % EOs and perfume contents are exported. India has the highest production of Japanese peppermint oil and Indian basil oil in the world. Uttar Pradesh and Andhra Pradesh are the largest producers of rose and tuberose oil, respectively, in India. Kerala, TN and Karnataka are major producers of jasmine oil in India. Market prices of EOs are depicted in Table.2.6 [64].

Table 2.6 Market prices of different EOs [64]

Essential oil	**Price (US$/ kg)**
Peppermint oil	10.85 – 27.14
Rose	2818.54 – 3932.85
Jasmine	1115.08
Ginger	51.56 – 56.99
Tuberose	2621.90 – 2687.45
Basil	8.14 – 9.16
Lemongrass	7.46 – 8.82
Pine	1.08 – 1.35

Turmeric	9.49 – 10.85
Sandalwood	814.25 – 882.11
Eucalyptus	5.42 – 8.14
Vetiver	366.41 - 434.27

2.1.5 GC-MS analysis of essential oil

GC-MS analysis of essential oil extracted from different aromatic and medicinal plant by various extraction methods is depicted in Table 2.7.

Table 2.7 GC-MS analysis of the essential oil extracted from aromatic and medicinal plants

Extraction Method	Essential oil Plant Material	Major Compounds	References
HD, SOX	Peppermint	Menthol (33.07–37.43%), menthone (9.49 25.21%), isomenthol (4.27–10.21%), isomenthone (4.51–6.06%) and eucalyptol (1.16–4.89%).	[65]
MAHD	Pomelo peel	Limonene (97.379%), ß-Mycrene (1.233%), α-Phellandrene (0.692%), and α -Pinene (0.49%)	[66]
	Common Sage	Eucalyptol (20.58%), ß-pinene (8.39%), camphene (6.88%), α-pinene (4.93%), ß-myrcene (3.83%), and sylvestrene (1.65%)	[67]
	Oregano	Thymol (58.40%), terpinene γ (12.59%), o-cymene (9.70%), terpinene α (3.42%) and ß-myrcene (2.24%)	

	Rosemary	Eucalyptol (39.38%), ß-pinene (11.25%), camphene (6.88%), α-pinene (3.53%), o-cymene (3.09%) and δ-3-carene (2.64%), Carvacrol (62.35%), terpinene γ (10.98%), o-cymene(8.73%), terpinene α (2.87%), ß-myrcene (2.36%), and α-pinene (3.53%)	
	Lavender	Linalyl acetate (26.61%), Linalool (19.71%), Lavandulol acetate (12.68%), Cedrelanol (3.65%) and α-Terpineol (3.61%)	[68]
	Eucalyptus obliqua	1,8-cineole (eucalyptol) (64.7%), α-pinene (12.6%), γ-terpinene (7.4%), limonene (3.9) and p-cymene (3.2%)	[69]
HD	Mace *(Myristicae arillus)*	β-Pinene (57.089%), 1R-α-Pinene (22.22%), γ-Terpinene (5.35%), and 4-Terpineol (5.15%)	[70]
MAHD, 300 W		β-Pinene (34.69%), 1R-α-Pinene (18.39%), 4-Terpineol (5.49%), and γ-Terpinene (3.44%)	
MAHD, 600W		β-Pinene (37.58%), 1R-α-Pinene (24.012%), γ-Terpinene (3.65%), and 4-Terpineol (3.12%)	
MAHD, 800W		β-Pinene (35.489%), 1R-α-Pinene (25.43%), 4-Terpineol (6.75%), and γ-Terpinene (4.71%)	

	S. lavandulifolia	Myrcene (41.6 %), α-pinene (33.0 %), β-phellandrene (12.2 %), β-pinene (5.1 %), sabinene (1.3 %) and α-phellandrene (1.3 %)	[71]
	Peppermint	Menthol (36.9%), menthone (28.8%) carveone (3.8%), neomenthol (3.8%), 1,8-cineole (3.8%) and limonene (3.29%)	[72]
HD	Thyme	Thymol (37.20 ± 2.86%), carvacrol (6.81 ± 0.05%), p-cymene (16.85 ± 0.08%), 1-octen-3-ol (2.69 ± 0.16%) and linalool (2.50 ± 0.14%)	[73]
MAHD		Thymol (40.20 ± 3.03%), carvacrol (6.84 ± 0.68%), p cymene (17.57 ± 0.78%), octen-3-ol (2.64 ± 0.31%), and linalool (2.43 ± 0.27%)	
HD	flowers of *Anaphalis contorta*	β-caryophyllene (19.2%), γ curcumene (17.5%), δ cadinene (10.2%), labda–7,14–dien–13–ol (4.8%), epi-α-cadinol (4.3%), bulnesol (4.3%), α-cadinol (3.8%), β-bisabolol (3.7%) and labda–8,14–dien–13–ol (3.3%).	[74]

2.2 RESEARCH GAP

The mentioned literature survey shows extensive work on conventional and advanced methods of essential oil extraction from aromatic and medicinal plants (Table 2.1-Table 2.7). However, less literature is available on performance and energy analysis of conventional steam distillation systems (biomass based) of oil extraction. Process parameters of biomass based conventional steam distillation system have not been optimized by any other researcher. Further, Solar energy integrated essential oil extraction system incorporating Scheffler reflector, boiler mounted at focus of reflector and automatic double axis tracking system has also not been analysed in terms of thermal, economic and environmental point of view by any researcher. Therefore, there is a need to develop and analysed a solar energy-based distillation unit for oil extraction from plant material to reduce environmental degradation and labour cost. The proposed systems will be analysed based on yield, energy, exergy, economic and environmental analysis in proposed research work.

2.3 RESEARCH OBJECTIVES

The research gap motivates to contribute ahead in this area to certain extent that can establish a milestone in the field of conventional (biomass based) and solar oil extraction techniques. Based on the research gap, certain research objectives have been framed that can be achieved by the experimental studies of the proposed systems that have been taken in the current research work as shown in Fig. 2.1

I. To analyze the performance of conventional steam distillation system based on productivity, essential oil yield

II. To do thermal analysis for conventional distillation system (biomass-based)

III. To develop a new solar energy integrated mentha (Peppermint) oil distillation system

IV. To do thermodynamic analysis of solar energy integrated mentha oil distillation system

V. To carry out economic and environmental analysis of conventional and solar energy integrated mentha oil distillation system

2.4 RESEARCH SCOPE

The analysis of biomass based conventional distillation system is quite required to reveal the next level of development in the field of essential oil techniques. Many more researchers have also worked in this area with certain research gaps and have been encountered in the form of a glimpse, as represented in Table 2.1-Table 2.6. So by fulfilling the research gap (performance evaluation, optimization of process parameters), one can improve the production of essential oil. The analysis of solar distillation system incorporating Scheffler reflector is quite required to reveal the next level of development in the field of essential oil extraction. Very few researchers have worked on solar distillation system for essential oil extraction from medicinal and aromatic plants as depicted in Table 2.1-Table 2.6. Based on the above study, it is being confirmed that biomass based conventional distillation system have not been analyzed based on performance, energy, economic and environmental point of view by any researcher so far. Further, solar distillation system with boiler mounted on focus of Scheffler reflector and double axis tracking have not been analyzed for thermodynamic, economic and environmental analysis by any researcher so far. Therefore, this novel proposed system (Fig. 2.1) has better research scope to increase the income of farmers and create job opportunities for youth.

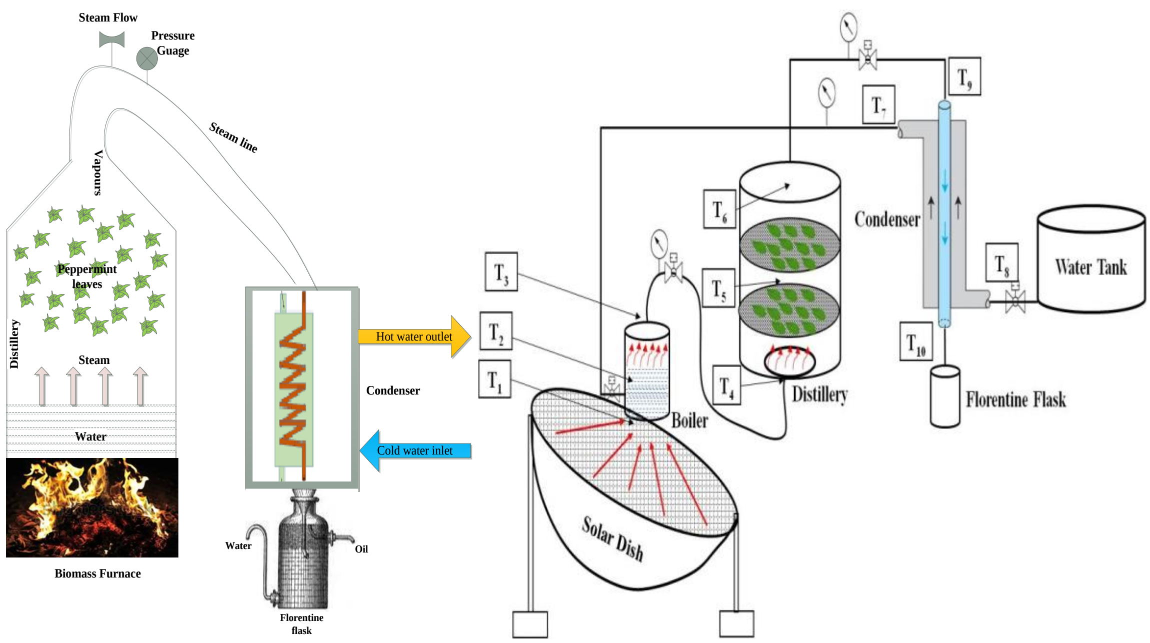


Fig.2.1 Schematic of proposed systems for present research study

2.5 RESEARCH CONTRIBUTION

Research contribution towards researcher and society in the context of essential oil production through an efficient, self-sustaining and cost-effective development is serving society in an eco-friendly manner. The entire set-up is designed accordingly to ensure its well developed and precise functioning throughout the day and thus life. Research contributions of present study are as follows:

I. Analysis of conventional distillation system shows performance improving potential and will be helpful for investors to setup an economical pilot plant for peppermint oil extraction.

II. Proposed model (solar distillation system) shows the furthermost benefits of double axis tracking and boiler mounted on focus of Scheffler reflector to collect maximum solar radiation on base of boiler resulting in reduced extraction time.

III. Proposed system doesn't need any biomass and fossil fuel, hence saving fuel cost that directly benefits in terms of the monetary value and additional manpower.

IV. Thermodynamic analysis of proposed system helps find out energy saving potential at different parts of system that directly improve the performance of system.

V. Proposed system produces a comparatively greater yield at a competitive price with lower embodied energy, establishment, running, and maintenance cost. Also, provides revenue through earned carbon credits from the international market, which benefits environmental health and indirect economic returns to the nation of mother land.

The next chapter sets the analytical methodology with sequential steps to achieve the research objectives as mentioned in chapter two. The exploration of conventional and solar distillation system for peppermint oil extraction with its detailed assumptions, experimental parameters, system description, and specifications have been done that are utilized while developing thermal model of the proposed systems. Then the detailed thermal model and characteristic equations along with the respective performance parametric observations are given in terms of mathematical expressions under the meteorological conditions of Jhansi (U.P) for conventional system and Delhi for solar distillation system for a clear archetypal day in the winter season of the month November.

CHAPTER: 3

METHODOLOGY

CHAPTER 3
METHODOLOGY

3.0 INTRODUCTION

This chapter explains the methodology that has been adopted to find the objectives. For a detailed discussion, it has been divided into two main sections. Section 3.1 explains detailed analysis of conventional distillation system and Section 3.2 the solar steam distillation system. The exploration of conventional and solar distillation system for peppermint oil extraction with its detailed assumptions, experimental parameters, system description, and specifications have been done that are utilized while developing thermal model of the proposed systems. Then the detailed thermal model and characteristic equations along with the respective performance parametric observations are given in terms of mathematical expressions under the meteorological conditions of Jhansi (U.P) for conventional system and Delhi for solar distillation system for a clear archetypal day in the winter season of the month November

3.01 METHODOLOGY TO BE ADOPTED

The working approach requires various parameters (solar radiation intensity, ambient temperature, relative humidity, temperature at different points of boiler and distillery, thermal conductivity, emissivity, heat absorption capacity, reflectivity, etc.) that are used in different governing equations, empirical relationships, energy balance equations, etc., for performance analysis of the proposed system. The brief of process followed is given as:

Step –I

In the very first step, Experimental observations of various parameters (temperature at various points of boiler and distillery, batch size of peppermint, fuel consumed, etc.) that have been recorded to determine the performance of conventional distillation system that is determined by governing equations for thermal efficiency, essential oil yield, and extraction efficiency based on previous studies and research gap identified by literature review.

Step-II

Optimization of process parameters like batch size and extraction time has been done using response surface methodology (RSM) to maximize the yield of conventional distillation system.

Step-III

Further, energy balance, mass balance for the convention distillation system have been carried out using the above findings. The evaluation of CO_2 emission-mitigations and net carbon credit are two components of the environmental analysis. Also, a detailed economic analysis of the proposed system has been carried out.

Step-IV

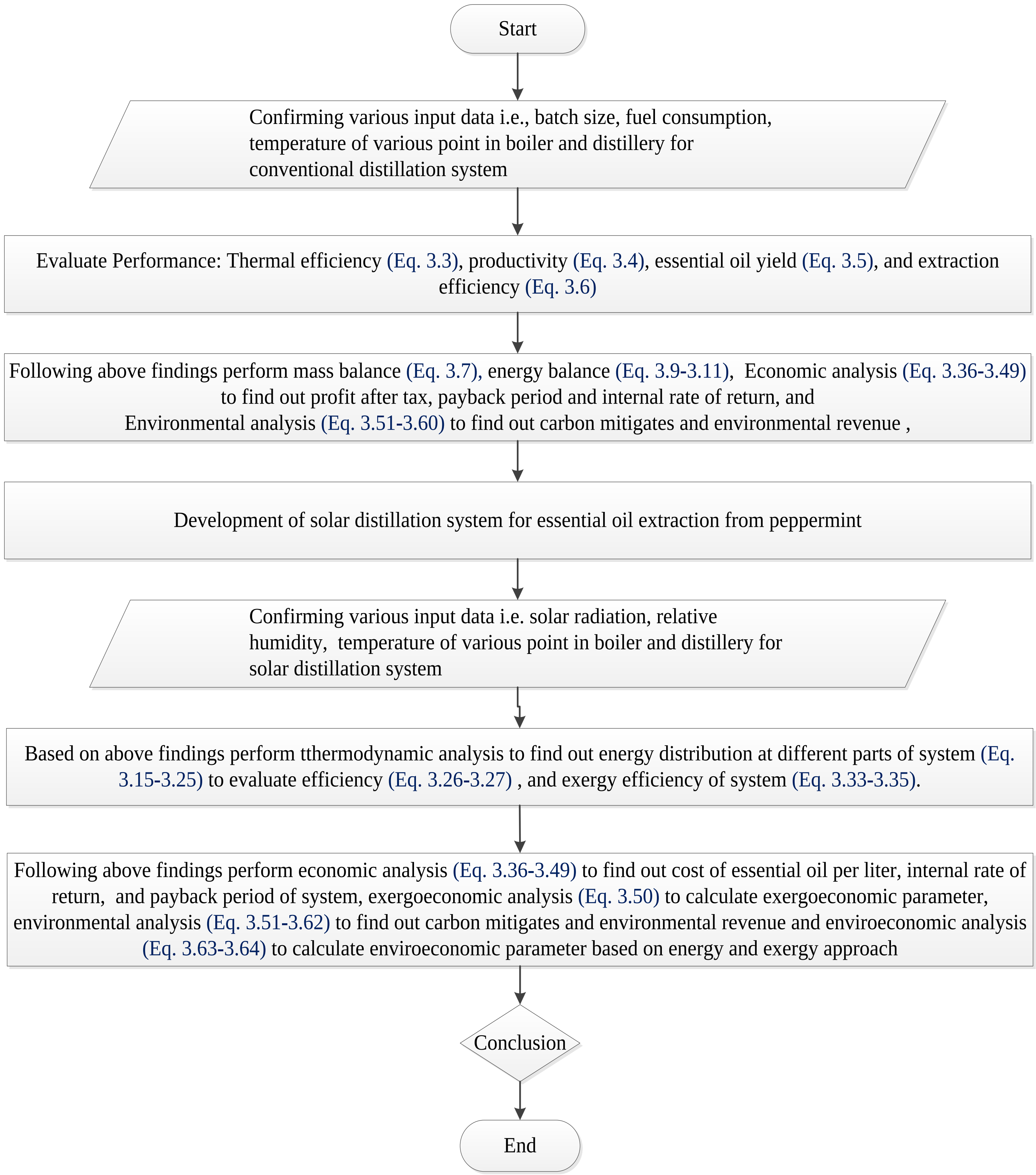
In the next step, Based on prior research and a research gap found by literature survey, a solar steam distillation system for extraction of essential oil has been developed. The initial idea for development of system is the response to solar radiation over the curved surface of reflector which is achieved by a double axis tracking mechanism.

Step-V

Thermal modeling of the proposed systems (solar steam distillation system) has been done that is basically governed by the energy balance equations applied at different segments, i.e., Scheffler reflector, Base of the boiler, inlet to distillery, distillery carried herb, inlet and outlet to condenser of the projected model.

Step-VI

Following the above step for evaluating the energy at Scheffler reflector, energy at base of boiler, and energy required for distillation of herb have been calculated for proposed system. Also, hourly yield and corresponding efficiencies for different parts of proposed systems are evaluated. Then additions to different energy and exergy quantities will provide the respective outputs of the proposed systems. Moreover, the effect of batch size on exergoeconomic and enviroeconomic parameters based on energy and exergy approach is computed.


Start
Confirming various input data i.e., batch size, fuel consumption, temperature of various point in boiler and distillery for conventional distillation system
Evaluate Performance: Thermal efficiency (Eq. 3.3), productivity (Eq. 3.4), essential oil yield (Eq. 3.5), and extraction efficiency (Eq. 3.6)
Following above findings perform mass balance (Eq. 3.7), energy balance (Eq. 3.9-3.11), Economic analysis (Eq. 3.36-3.49) to find out profit after tax, payback period and internal rate of return, and Environmental analysis (Eq. 3.51-3.60) to find out carbon mitigates and environmental revenue ,
Development of solar distillation system for essential oil extraction from peppermint
Confirming various input data i.e. solar radiation, relative humidity, temperature of various point in boiler and distillery for solar distillation system
Based on above findings perform tthermodynamic analysis to find out energy distribution at different parts of system (Eq. 3.15-3.25) to evaluate efficiency (Eq. 3.26-3.27) , and exergy efficiency of system (Eq. 3.33-3.35).
Following above findings perform economic analysis (Eq. 3.36-3.49) to find out cost of essential oil per liter, internal rate of return, and payback period of system, exergoeconomic analysis (Eq. 3.50) to calculate exergoeconomic parameter, environmental analysis (Eq. 3.51-3.62) to find out carbon mitigates and environmental revenue and enviroeconomic analysis (Eq. 3.63-3.64) to calculate enviroeconomic parameter based on energy and exergy approach
Conclusion
End

3.1 CONVENTIONAL DISTILLATION SYSTEM

3.1.1 Experimental setup description

Conventional distillation system consists of four parts: furnace, boiler, distillation unit and condenser. Experiments were performed for different batch sizes for three different days.

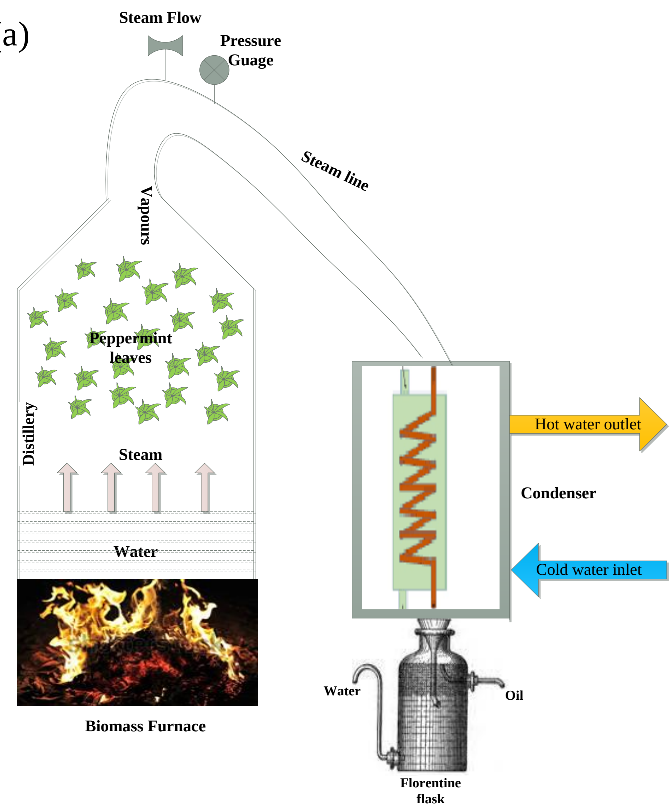
Furnace: Furnace was made up of bricks and concrete with cuboid shape (1.82 meter length, 2.27 meter width, and 0.076 meter height). Heat is generated in the furnace by burning biomass (wood), which is transferred to the boiler.

Boiler: it was made up of iron with length of 2.13 meter, width of 2.13 meter and height of 0.063 meter. Boiler completes the process of water evaporation. Water in the boiler is heated up to the boiling point and converted into steam. Around 300-500 L water is required to complete one cycle. It is placed above the furnace.

Distillery: The distillery was made to handle enough peppermint plant batch sizes. Extraction unit was cylindrical in shape, with a diameter of 1.82 meter and a height of 3.04 meter. It is constructed of stainless steel with a thickness of 2 centimeter. Two nets with a 1.80 diameter were placed inside the extraction unit, one at the bottom and the other at mid-height from the bottom, to place peppermint plants batch and allow steam to separate volatile oil easily. Distillery includes two openings: one at bottom to supply steam from the boiler to distillery, which passes inside peppermint plants to separate volatile oil, and another at top to supply steam from essential oil to the condenser to separate oil.

Condenser: it was made up of stainless steel with 2.13 meter length, 1.52 width, and 1.52 meter height. Steam intake, cooling water inlet, condensed water outlet and cooling water outlet were the four openings on the condenser. Cooling water was delivered to the condenser unit via a water tank controlled by a hand valve. It was also connected to the extraction unit, which received steam and oil, which was then condensed to generate volatile oil. A funnel tube was used to collect the volatile oil that had been extracted. Oil floats to the top because oil is less dense than water. Schematic and photographic view of experimental setup for conventional distillation system is shown in Fig.3.1 (a) and Fig.3.1 (b), respectively.

(a)



(b)

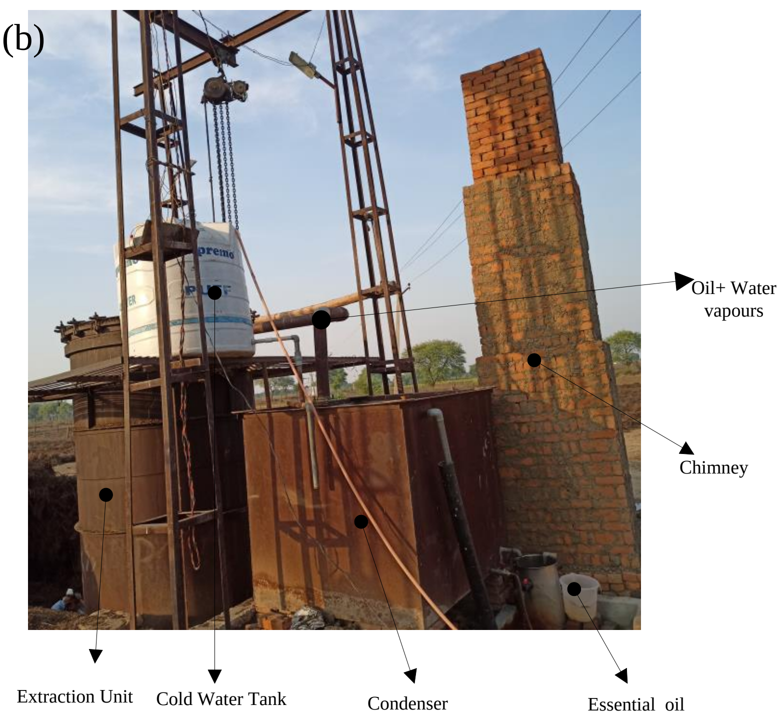


Fig.3.1 (a) Schematic and (b) Photographic view of conventional distillation system

Table 3.1 Description of conventional distillation system

S. No.	Name of component	Material	Size (meters)	Working Description
1	Furnace	Bricks and concrete	1.82×2.27×0.076	Heat is generated by burning biomass (wood) in the furnace, and transferred to the boiler.
2	Boiler	Iron	2.13×2.13×0.063	Boiler completes the evaporation process of water. Water in the boiler is heated up to the boiling point and converted into steam. Water required to complete one cycle was about 300-500 L. It is placed above the furnace.
3	Distillery	Stainless steel	Height = 3.04 Diameter = 1.82	Peppermint leaves are placed in two trays above the boiler in the distillery. One is kept at bottom and another at mid-height of distillery column. There are two openings in the distillery; one is at the bottom and the other is at distillery. Opening at the bottom is used to pass the steam generated in the boiler to leaves of Peppermint, while top opening is used to pass the evaporated oil and water vapors to the condenser. The holding capacity of the distillery is about 1800 -2000 kg batch size.
4	Condenser	Stainless steel	2.13×1.52×1.52	Mixture of oil and water vapors generated in the distillery is transferred to the condenser through

the connection pipe. A water tank is attached to the condenser for a continuous supply of water. Two outlets are used in a condenser to remove the hot water. Oil and water are separated in Florentine flask.

3.1.2 Observations

Conventional steam distillation system (CSD) is installed at Birpura village, Jhansi, India (25° 36N′18.40″E). Experiments were performed for one complete cycle over three days in November 2020 for various batch sizes of the entire plant (1500 kg, 1700kg, and 1900 kg). Time duration of the experiments was the same for all three days (03:00 pm to 08:00 pm). Yield, mass of fuel, temperatures at different positions in boiler, and steam temperature at distillery outlet using thermocouples, Infrared thermometers and digital temperature indicators are recorded during the experimentation. A beaker (measuring scale marked on upper side) and digital weighing machine measure the oil yield and mass of wood fuel, respectively. Dry branches of mango trees were used as fuel for burning.

3.1.3 Uncertainty Analysis

Uncertainty is the most important factor in determining the accuracy of the experimental data. There are two types of data uncertainty: type A is random error, and type B is a systematic error. Type B uncertainty is calculated here because data is uniformly distributed. The standard uncertainty of the instruments used for observation is calculated from Eq. (3.1). The accuracy and standard uncertainty of the instruments used are given in Table 3.2.

$$Standard\ Uncertainty = \frac{Accuracy\ of\ instrument}{\sqrt{3}} \tag{3.1}$$

Table 3.2 Technical specification of the instruments used in the experiments [75]

Instruments	Observed Parameter	Accuracy	Range	Standard Uncertainty	Uncertainty in observed parameter
Thermocouple (TC-KT-02)	Temperature	±0.1°C	-20 to 200 °C	0.057°C	±0.25°C
Solarimeter (PMV-210)	Solar radiation	10 W/m^2	0-2000 W/m^2	5.77 W/m^2	±5.78 W/m^2
Digital Hygrometer (MEXTECH TM-1)	Ambient temperature and relative humidity	3%	5-85%	1.73%	±1.7%
Weight machine (HN-283)	Weight of medicinal plants	0.1gm	0.0001 to 10 kg	0.05 gm	±0.0005

When any function Y depends on the no of input parameters or independent variables, then the uncertainty in the measured value of the function Y is given by Eq. (3.2)[75]:

$$U(Y) = \left[\left(\frac{\partial Y}{\partial x_1}\right)^2 u^2(x_1) + \left(\frac{\partial Y}{\partial x_2}\right)^2 u^2(x_2) + \cdots \dots \dots + \left(\frac{\partial Y}{\partial x_n}\right)^2 u^2(x_n)\right]^{1/2} \quad (3.2)$$

where, U(Y) is the uncertainty in the measured function and $u(x_1)$……u (x_n) is the uncertainties in the independent variables (x_1……x_n), affecting the function Y

3.1.4 Performance Evaluation

Performance analysis of conventional steam distillation system is carried out in this section. It is useful for energy-efficient operation. Following parameters are considered to evaluate the performance of conventional steam distillation system:

a. Thermal efficiency of conventional distillation system

Efficiency is the ratio of output to input. The yield of Peppermint oil is the output and heat energy of wood fuel is the input in this case. Thermal efficiency of the system is evaluated as Eq.3.3 [76]:

$$\eta = \frac{\dot{m} \times L}{m_f \times C.V} \times 100 \quad (3.3)$$

b. Operational performance of conventional distillation system

System productivity, essential oil yield and extraction efficiency are estimated to conduct the operational performance of the conventional distillation system.

- **System Productivity**

Total amount of oil extracted from Peppermint leaves is the system productivity. Hourly system productivity is evaluated from Eq.(3.4) [15,30]:

$$P = \frac{V}{t} \quad (3.4)$$

Cumulative system productivity is evaluated by recording the yield (L) at the end of the extraction stage.

- **Essential oil yield**

Essential oil yield of the system is defined as the ratio of mass of extracted oil to mass of the plant per batch size and determined by the following Eq.(3.5) [15,29,30]:

$$EOY = \frac{m_{oil}}{m_{plant}} \quad (3.5)$$

In Eq.3.5, $m_{oil}$is the mass of oil in kg and m_{plant} represents a mass of plant per batch size in kg.

- **Extraction efficiency**

Extraction efficiency is the ratio of oil mass to maximum mass of oil per plant batch size. Efficiency of oil extraction is evaluated by 100 g of Peppermint carrying 1 ml of volatile oil and calculated from Eq.(3.6) as [15,30]:

$$\eta_{extraction} = \frac{m_{oil}}{m_{\max oil}} \quad (3.6)$$

In Eq.3.6, $m_{\max oil}$ represents the maximum mass of oil per plant batch size in kg.

3.1.5 Mass balance

Mass balance was performed on the process units based on the plant processing capacity of 20 litres of essential oil per batch, 1900 kg of leaves input, 300 minutes of extraction time, 1000 litres of water requirement, and 592.93 kg of steam production. As a result, Eq. (3.7) provides the mass balance for a steady state batch operation without any chemical reaction, which was implemented to all unit operations beginning with extracting unit as depicted in Fig.3.2.

$$\text{Mass input} = \text{Mass output} \tag{3.7}$$

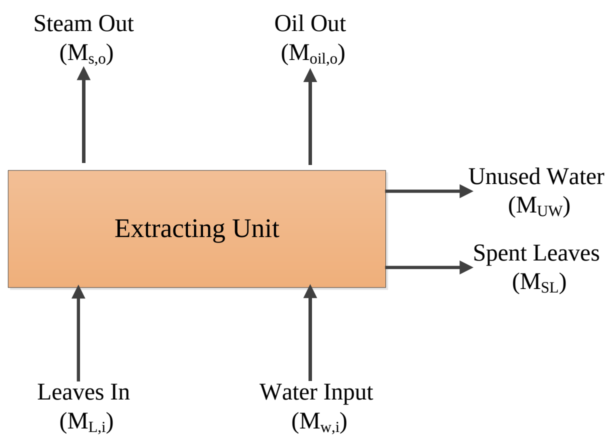


Fig.3.2 Mass balance over extracting unit

Fig.3.3 illustrates the mass balance in condenser unit where steam and oil mixture flow through the tubes while cooling water in the shell.

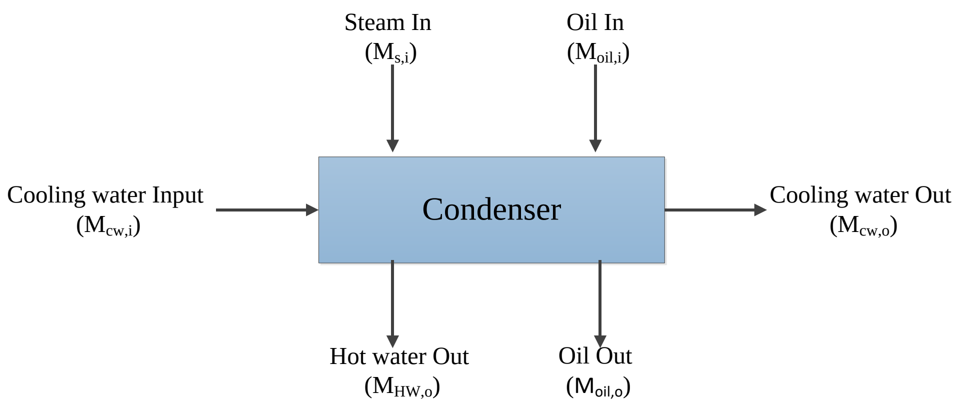


Fig.3.3 Mass balance over condenser

Condensate from condenser was fed into Florentine flask where water and oil were separated due to density difference and Fig.3.4 shows mass balance in Florentine flask.

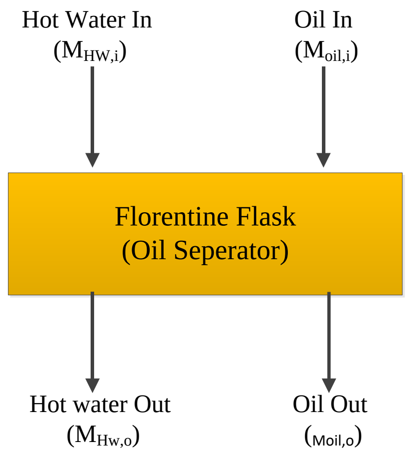


Fig.3.4 Mass balance over Florentine flask

3.1.6 Energy Balance

The quantity of fuel consumed per batch size was calculated by adding the weight of wood consumed per hour for complete operation cycle. Total Energy consumption (Qs) per batch size for complete operation cycle is calculated as [77]:

$$Q_s = m_f \times CV \tag{3.8}$$

a. Energy balance over extracting unit

Energy balance over extracting unit shown in Fig.3.2 for a batch operation without any chemical reaction is presented as:

$$Q_s = Q_W + Q_{evap} + Q_{oil} + Q_{leave} + Q_{tank} + Q_{lost} \tag{3.9}$$

In Eq. (3.9), Q_w, Q_{evap}, Q_{oil}, Q_{leave}, Q_{tank} and Q_{lost} represent heat gained by water, heat required for water evaporation, heat gained by oil, heat gained by leaves, heat lost to environment and heat gained by extracting unit, respectively. These heat gains are calculated as:

$$Q_W = M_W C_W \Delta T_W \tag{3.9a}$$

$$Q_{evap} = M_s L \tag{3.9b}$$

$$Q_{oil} = M_{oil} C_{oil} \Delta T_{oil} \tag{3.9c}$$

$$Q_{leave} = M_L C_L \Delta T_L \quad (3.9d)$$

$$Q_{lost} = 0.3Q_s \quad (3.9e)$$

Heat gained by extracting unit is calculated from Eq. (3.9) as:

$$Q_{tank} = Q_s - Q_W - Q_{evap} - Q_{oil} - Q_{leave} - Q_{lost} \quad (3.9f)$$

b. Energy balance over condenser

In condenser depicted in Fig.3.3 and under steady state heat supply, energy released by mixture of steam and oil is equals to energy absorbed by cooling water.

$$Q_{s,o\ mixture} = M_{CW} \times C_{CW} \times (T_o - T_i) \quad (3.10)$$

c. Energy balance in Florentine flask

Energy balance in Florentine flask depicted in Fig.3.4 was performed based on the assumption that separation of the water and oil was based on density difference and performed at room temperature (25°C) indicating there was no temperature gradient.

$$M_{W,i}H_{W,i} + M_{oil,i}H_{oil,i} = M_{W,o}H_{w,o} + M_{oil,o}H_{oil,o} \quad (3.11)$$

3.1.7 Extraction time (Te)

The extraction time was calculated using a stopwatch by measuring the time for charging the leaves and capping the tank cover (T1), the collection of the first drop of the steam oil mixture (T2), the interval between the first and last drops of the steam oil mixture (T3), and the off-loading of the spent leaves (T4) [77].

$$T_e = T_1 + T_2 + T_3 + T_4 \quad (3.12)$$

3.1.8 Economic analysis

Mathematical expressions used for economic study of conventional steam distillation (CSD) system of essential oil extraction have been presented in section 3.3 of present thesis.

3.1.9 Environmental analysis

Environmental analysis of CSD system can be carried out in two ways: (i) by calculating CO_2 emissions by direct burning of biomass (ii) in terms of carbon trading, as CO_2 can be emitted from CSD system by direct burning of biomass and by materials during its fabrication.

a. CO_2 emissions by direct burning of biomass

CO_2 emissions by direct burning of biomass depend on energy consumption as energy consumption is directly proportional to mass of fuel burned. Energy consumption and carbon dioxide (CO_2) emissions are determined to assess the environmental impact. The energy consumption for CSD method was calculated as [39]:

$$E_c = E \times t \tag{3.13}$$

$$E = m_f \times C.V \tag{3.13a}$$

According to Drinic et al. (2020), 800 g of CO_2 is rejected to the environment by burning coal or fossil fuel to produce 1 kWh. CO_2 emissions can be calculated by following equation [39]:

$$E_{CO_2} = (E_c \times 800)/1000 \tag{3.14}$$

b. Environment analysis in terms of carbon trading

Equations or mathematical expressions used in environmental study of CSD system in terms of carbon trading have been presented in section 3.5 of present thesis.

3.2 SOLAR STEAM DISTILLATION SYSTEM

Conventional methods are unsuitable from an environmental point of view since they emit aerosols and greenhouse gases. These methods have low efficiency and higher costs due to longer extraction time and higher energy consumption. Cooking, pasteurization, desalination, and extraction are just a few of the thermal applications where solar energy is used. As a result, solar energy is a suitable alternative to replace CSD oil extraction technologies, as it is both inexhaustible and environmentally friendly. The solar steam distillation method is an advanced oil extraction SD method [13,14].

3.2.1 Experimental setup and observations

SSDS is located at roof top of Centre for Energy and Environment, Delhi Technological University, Delhi (28.7041° N, 77.1025° E). As reflector inclination depends on latitude of place, the reflector's rotation axes are set to the local latitude angle (28.7041°), ensuring that the reflector's rotation axis and the earth's rotation axis are parallel. Solar distillation system mainly consists of four parts named Scheffler reflector (10 m^2), boiler, distillation unit, condenser, and

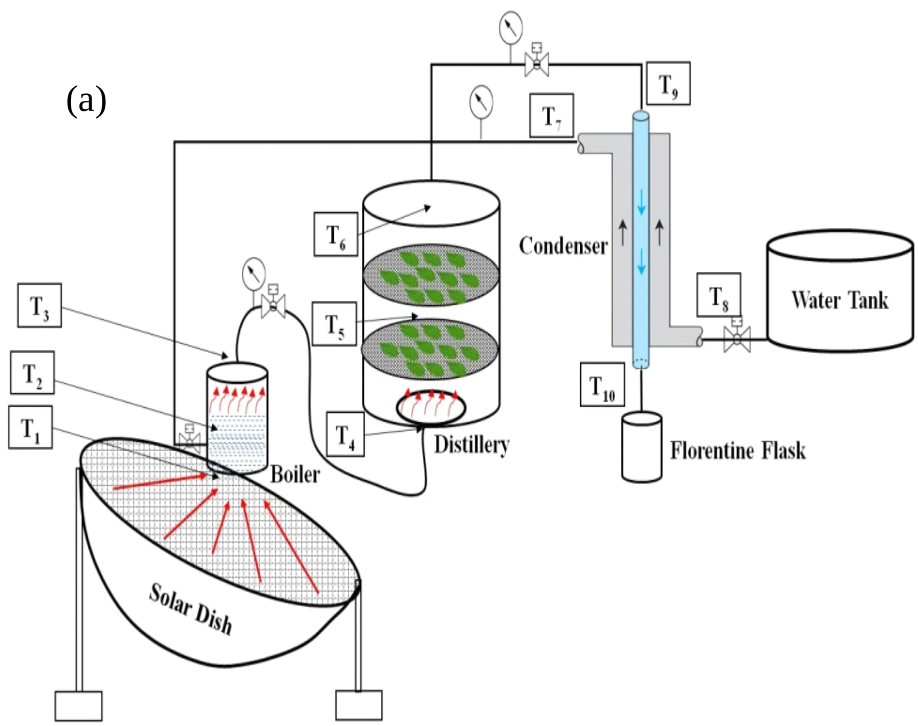
Florentine flask. Scheffler reflector is prepared by pasting mirrors of glass on aluminium frame structure. An iron pole is fixed in concrete structure to bolt the Scheffler reflector. Double axis tracking system is installed to improve efficiency of system. Four light difference resistor (LDR sensors) and two motors are used for tracking the sun. LDR sensor sends signal to microcontroller that rotates the motors in suitable direction. One motor is used for east to west (left-right) motion of reflector and other one for north to south (up-down) motion of reflector. Boiler is made up of stainless steel material with capacity of 15 litre of water and insulated with glass wool (2.5 cm). Solar radiations fall on Scheffler reflector and are reflected to the base of boiler. The water in the boiler gets heated up by radiation and converted into steam. Boiler is connected to distillation unit by silicon pipe with diameter of 1.25 cm. silicon pipe is also insulated by glass wool with thickness of 2.5 cm. Peppermint plants are placed in distillery at the two nets that are located at bottom and middle of distillery. The steam passes through peppermint leaves and oil evaporates from this steam. Distillery is connected with condenser and mixture of steam and oil is condensed in the condenser. Oil and water are separated in Florentine flask. Oil remains at the top as water density is higher than oil. Schematic and photographic view of SSDS is shown in Fig.3.5. Detailed description of SSDS is depicted in Table 3.6.

Table 3.3 Detailed description of SSDS

S.No.	Components	Size (m)/ Capacity	Materials
1.	Solar Scheffler reflector	Diameter = 3.6 Aperture area = 10 m^2	Aluminium
	Plane mirrors	No of mirrors = 6400 (0.05×0.05)	Glass
2.	Boiler	Capacity = 15 litters Diameter = 0.334 Height = 0.56 Thickness = 0.004	Stainless steel

3.	Distillery	Diameter = 0.66 Height = 0.86 Thickness = 0.0008	Stainless steel
4.	Condenser (counter flow plate type heat exchanger)	Inlet diameter = 0.012 Outlet diameter = 0.012	Mild steel

(a)



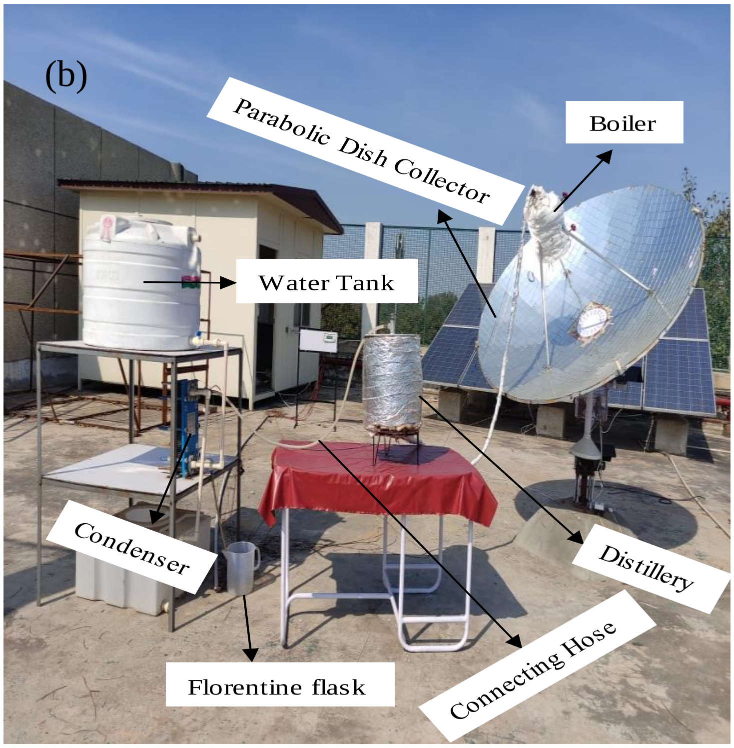


Fig.3.5 (a) Schematic and (b) photographic view of solar distillation system

Experiments were performed for different batch size (2, 4 and 6 kg) of peppermint in May 2021 for three different days. Various observations were made during experimentation such as temperature, pressure and steam flow rate at different point. K-type thermocouple was used to measure the temperature at base of boiler and all other thermocouples were PT-100 type. Temperature at different points of boiler was measured using T_1, T_2 and T_3 thermocouples. Thermocouples T_4, T_5, and T_6 were used to measure the temperature at various positions in distillery. Temperature of water and steam at inlet and outlet of condenser was measured by T_8, T_7, T_9, and T_{10} thermocouples, respectively. Two pressure gauges are used to measure boiler outlet and distillery outlet pressure. All the thermocouples and pressure gauges are connected to a 16-channel data logger which records temperature and pressure.

3.2.2 Energy analysis

Energy distribution at different parts, steam line and condenser losses, performance assessment and exergy analysis of solar distillation system has been presented in this section.

a. Distribution of energy at Scheffler reflector

Energy is absorbed and distributed over Scheffler reflector in the form of reflected radiation. The reflectivity of the material determines the amount of energy reflected. As a result, the energy generated by reflector is represented as [13]:

$$E_{pr} = E_i \times R_m \tag{3.15}$$

$$E_i = I_g A_s \cos(43.25 \pm {}^{\delta}/_{2}) \tag{3.15a}$$

$$\delta = ({}^{180}/_{\pi})[(0.006918 - 0.399912)\frac{\cos(n-1)2\pi}{365} + 0.070257\frac{\sin(n-1)2\pi}{365} - 0.006758\frac{cos2(n-1)2\pi}{365} + 0.000907\frac{\sin(n-1)2\pi}{365} - 0.002679\frac{cos3(n-1)2\pi}{365} + 0.00148\frac{\sin(n-1)2\pi}{365} \tag{3.15b}$$

b. Energy distribution at bottom of boiler

The components of reflector are intended to reflect and disperse all rays to bottom of boiler; the energy assessable at bottom of boiler is expressed as [13]:

$$E_b = E_{pr} \times F_b \tag{3.16}$$

Thermal energy available to generate steam in boiler is calculated as:

$$E_{cond,b} = E_b \times \alpha_b \tag{3.17}$$

c. Total thermal energy during distillation

Total heat energy required for distillation of herb can be calculated as [13,14]:

$$E_{d,h} = \frac{[(m_w + M_w m_h)C_w + m_h(1 - M_w)C_f] \times \Delta T + X m_s h_{fg}}{3600} \tag{3.18}$$

$$X = \frac{[{}^{(m_{wc}C_w + m_c C_c)(T_{2c} - T_{1c})}/_{m_{sc}} - C_w(T_s - T_{2c})]}{h_{fg}} \tag{3.18a}$$

d. Total losses from receiver

The heat energy lost to environment by convection and radiation is total loss from receiver. Except for the receiving aperture, all of the receiver's surfaces are considered to be insulated in this article, and heat energy lost from insulation surfaces to surrounding is minimal. Various studies have been conducted to calculate heat energy lost from the receiver due to force and free convection. Geometrical and operational conditions must be addressed while determining the heat transfer coefficient. Madadi et al. provided a correlation for computing the Nusselt number that can be utilized here; it is expressed as [54]:

$$Nu = 0.0196(Ra^{0.41}P_r^{\ 0.13}) \tag{3.19}$$

Where Nusselt number and Rayleigh number are defined as:

$$Nu = \frac{hL_c}{K} \tag{3.19a}$$

$$Ra = \frac{g\beta(T_r - T_a)L_c^{\ 3}}{\vartheta\alpha} \tag{3.19b}$$

Convective loss from receiver can be determined as [54]:

$$\dot{Q}_{loss,conv} = hA_r(T_r - T_a) \tag{3.20}$$

The surface of entire internal cavity can be viewed as one surface and surrounding enclosure as another surface if condition of wall is assumed to be isothermal and emission of receiver wall is constant for all portions of the wall. Radiative loss from receiver can be determined as:

$$\dot{Q}_{loss,rad} = \sigma A_r \epsilon_{eff}(T_r^{\ 4} - T_a^{\ 4}) \tag{3.21}$$

Where, effective emissivity of body can be determined as:

$$\in_{eff} = \frac{1}{1 + (\frac{1-\varepsilon}{\varepsilon})\frac{A_{r,w}}{A_r}} \tag{3.21a}$$

e. Steam line and condenser's energy distribution

Most studies concentrate on energy lost in solar still but lost energy in steam line could be significant and should not be neglected. This activity solves the problem by comprehensively examining the condenser and steam line. The cooling water circulates against steam in the condenser. This flow arrangement is more efficient, according to the results. Furthermore, cooling water inlet temperature must be as cold as possible to maximize the heat transmitted. The temperature differential between the condenser's water inlet and exit is minimized in this situation, resulting inlet energy to condenser (cooling energy) [13]:

$$E_{l,c} = \dot{m}_c(T_{o,c} - T_{i,c})l_{phase-latent} \quad (3.22)$$

Energy requirement to condense entire vapour and found on the outside of the condenser can be expressed as follows:

$$E_{o,c} = \frac{m_v L_v}{3600} \quad (3.23)$$

Energy inlet to condenser from outlet of steam line pipe can be expressed as [13]:

$$E_{o,sl} = E_{o,c} + E_{l,c} \quad (3.24)$$

Therefore, energy loss in steam line pipe can be calculated as [13]:

$$E_{l,sl} = E_{cons,w} - E_{o,sl} \quad (3.25)$$

3.2.3 Assessment of the solar distillation system's performance

Main equation for determining efficiency of a SSDS by considering energy lost in steam line and condenser is expressed as [13]:

$$\eta_s = \eta_{optical} \times \eta_{still} \times \eta_{sl} \times \eta_c \quad (3.26)$$

Where

$$\eta_{optical} = \lambda \times \rho \times \tau \times \alpha \times \gamma\ cos\theta \quad (3.26a)$$

$$\eta_{still} = \frac{E_{d,h}}{E_{cond,b}} \quad (3.26b)$$

$$\eta_{sl} = \frac{E_{o,sl}}{E_{cons,w}} \quad (3.26c)$$

$$\eta_c = \frac{E_{o,c}}{E_{o,sl}} \quad (3.26d)$$

Furthermore, the distillation system's efficiency is defined as the ratio of essential oil extracted to energy consumed (mL/kWh) and expressed as:

$$\eta_{EO} = \frac{V_{EO}}{\eta_{optical}\eta_{still}\eta_{sl}\eta_c E_i} \quad (3.27)$$

Munir and Hensel have also given the relation to calculate the efficiency of solar distillation system as [14]:

$$\eta_s = \frac{10^3 E_{d,h}}{\int_{t=0}^{t=t_o} I_{g,ave} A_s dt} \quad (3.28)$$

Where

$$A_s = (\pi ab - 0.1)\cos(43.23 \pm {}^{\delta}/_{2}) \quad (3.28a)$$

Efficiency of Scheffler reflector is defined as the ratio of useful energy to incident energy on reflector’s aperture from sun and calculated as [54]:

$$\eta_{reflector} = \frac{\dot{Q}_u}{\dot{Q}_s} = \frac{E_{cond,b}}{E_i} \quad (3.29)$$

Solar irradiance varies throughout time, but it can be regarded as constant for short durations, allowing the system to be treated as a quasi-steady state system. Under steady-state conditions, the quantity of useable heat energy delivered by the collector system equals energy received by heat transfer fluid. Absorbed energy is computed by subtracting energy received by receiver from total losses from receiver to environment [54].

$$\dot{Q}_u = \dot{Q}_r - \dot{Q}_{loss} \quad (3.30)$$

Optical efficiency is defined as the ratio of energy reflected from aperture of reflector to the energy incident on reflector’s aperture and used to determine the energy reflected from reflector [54].

$$\eta_{optical} = \frac{\dot{Q}_r}{\dot{Q}_s} \quad (3.31)$$

Rate of useful heat gain based on the fluid temperature difference can be calculated as [54]:

$$\dot{Q}_u = \dot{m} C_w (T_o - T_{in}) \quad (3.32)$$

3.2.4 Exergetic analysis

Exergy is the maximum amount of useful work obtainable when system is in equilibrium with its surroundings. The use of exergy analysis in solar parabolic concentrator systems is essential to minimize exergy losses and achieve optimal design parameters [54]. Exergy is the portion of energy that is useful. Solar exergy rate released by the sun to the reflector depends on the exergy balance of SSDS for steady flow conditions ($E_{x,in}$). It also depends on the exergy needed to heat up water in boiler ($E_{x,out}$) [13,14].

$$Ex_{,i} = I_g A_a [1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)]\Delta t \quad (3.33)$$

$$Ex_{,o} = mC_p[(T_o - T_i) - T_{amb}\ln(\frac{T_0}{T_i})] \quad (3.34)$$

Exergy efficiency of solar distillation system for peppermint oil extraction is defined as the ratio exergy needed for distillation to the exergy of sun:

$$\%\, \eta_{ex} = \frac{Ex_{,o}}{Ex_{,i}} \times 100 \quad (3.35)$$

3.3 ECONOMIC ANALYSIS

Relevant equations for determining annual operating cost, return on investment, and profit after tax, internal rate of return, return on equity, and project payback period were used as analytical tools for the economic study of conventional steam distillation system and solar steam distillation system.

a. Total investment of system (TC)

Total direct cost of system (TDC) and total indirect cost of system (TIC) are both included in the total cost of system (TC) and is calculated as [60]:

$$\mathrm{TC} = \mathrm{TDC} + \mathrm{TIC} \quad (3.36)$$

The purchase cost (PC) factor method was used to evaluate TDC of system. This process involves assigning a carefully chosen factor to each component which when multiplied by total cost of the equipment, gives an estimated cost of system. Hence;

$$\mathrm{TDC} = \mathrm{PC} + \mathrm{A}\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{f_i} \quad (3.36a)$$

Where, PC = purchase cost of physical equipment

A = Assigned factor (5% - 40%)

fi = Processing cost, installation cost, instrumentation cost of each equipment and electrical facilities

TIC is determined by sum of total cost of engineering design and construction which were assigned 25 % and 30% of TDC, respectively.

b. Cost of essential oil per liter (CPL)

The primary calculation parameters that are typically employed in the cost analysis of the distillation system units are the capital recovery factor (CRF), fixed annual cost (FAC), sinking fund factor (SFF), annual salvage value (ASV), average annual productivity (M), and annual cost (AC). The parameters described above can be represented as [78]:

$$CRF = {i(1+i)^n}/{[(1+i)^n - 1]} \tag{3.37}$$

$$FAC = TC \times (CRF) \tag{3.38}$$

$$ASV = SSF \times S \tag{3.39}$$

$$S = 0.2 \times TC \tag{3.40}$$

$$SSF = {i}/{[(1+i)^n - 1]} \tag{3.41}$$

$$UAC = FAC + AMC - ASV \tag{3.42}$$

$$CPL = \frac{UAC}{M_{oil}} \tag{3.43}$$

c. Annual operating cost

The system's annual operating cost (AOC) is composed of raw material costs (peppermint plants), total annual production costs (TAPC), and utilities costs [60,79]. Therefore;

$$\text{AOC} = \text{Cost of raw material} + \text{TAPC} + \text{utilities cost} \tag{3.44}$$

Personnel expenses, system maintenance, local taxes, supervision, insurance, plant overhead, sales taxes, and R&D costs were all included in the TAPC.

d. Profit cost analysis

The difference between sales revenue (SR) and operating cost (OC) is the operating profit (OP) (US$) and is calculated as [60,77]:

$$\text{OP} = \text{SR} - \text{OC} \tag{3.45}$$

Difference between operating profit (OP) and sum of depreciation (D) and tax (T) is known as profit after tax (PAT) and is calculated as:

$$\mathrm{PAT} = \mathrm{OP} - (\mathrm{D} + \mathrm{T}) \tag{3.46}$$

Where:

$$\mathrm{D} = (\text{cost of system} - \text{salvage value})/\text{economic life span of system} \tag{3.46a}$$

e. Return on investment (ROI)

Based on the various projections, the project's return on investment (ROI) was calculated as the ratio of PAT to total investment (I) in the project [77].

$$\mathrm{ROI}\ (\%) = {}^{\mathrm{PAT}}/_{\mathrm{I}} \tag{3.47}$$

f. Payback period (PBP)

The PBP is the time to return the project's investment, and it is expressed mathematically as [77,80];

$$\mathrm{PBP} = \mathrm{I}/\mathrm{ACF} \tag{3.48}$$

Where, I and ACF are investment (US$) and annual cash flow (US$).

e. internal rate of return (IRR)

IRR of the project is determined as [60,77]:

$$-\mathrm{I} + \sum_{i=1}^{n} \frac{\mathrm{nACF}}{(1+\mathrm{IRR})^{n}} = 0 \tag{3.49}$$

3.4 EXERGOECONOMIC ANALYSIS

Exergoeconomic analysis is a form of economic analysis that is based on exergy approach. It combines exergy analysis with traditional cost analysis to improve the effectiveness of energy systems. The goal of this analysis is to determine the cost-effective structure and values as well as to assist designers in coming up with cost-effective strategies to improve the system performance. Traditionally, exergy loss per unit cost has been estimated as exergoeconomic parameters in order to minimize loss. Since there is no penalty for exergy loss because solar radiation, which is an input in the case of solar systems, is provided without cost therefore exergoeconomic parameter does not appear to be sustainable with the solar systems.

Moreover, solar radiation cannot be controlled due to its dependency on environmental conditions[81]. Hence, it is impossible to compare different solar distillation systems using the same input. As a result, the exergoeconomic parameter based on exergy gain in order to increase the exergy gain was used. The exergoeconomic parameter (R_{ex}) is mathematically expressed as [82]:

$$R_{ex} = \frac{E_{x,o}}{UAC} \tag{3.50}$$

3.5 ENVIRONMENTAL ANALYSIS

A common designation for the environmental assessment framework is the embodied energy approach because it is versatile and capable of comparing systems easily. The amount of energy used to produce all of the materials and system components is referred to as embodied energy [83]. With the help of this type of examination, materials with high embodied energy values can be identified and then replaced with more favourable ones. However, the fundamental drawback of this type of study is the lack of understanding of system boundaries. For the construction of the solar distillation unit, materials like glass wool, stainless steel, mild steel, brass, and aluminium are used. Energy from coal-based power plants is used throughout the construction and development of the solar distillation unit. However, only renewable solar thermal energy is used during operation; as a result, energy spent on the system can be recovered.

3.5.1 Energy payback time (EPBT)

Assessment of the energy payback time (EPBT) for energy systems is essential to validate its sustainability since the implementation of systems can't be a reasonable assessment if the energy produced from systems is lesser than the energy used for the fabrication of the system [81]. The amount of time needed to recover the energy used (embodied energy) during the manufacturing of the components for SSDS is referred to as the energy payback time (EPBT). EPBT can be determined as [84,85]:

$$EPBT = \frac{E_{emb}}{E_{en,o}} \tag{3.51}$$

Annual thermal energy output obtained from distillation system can be determined as [86]:

$$E_{en,o} = \frac{\dot{m}L}{3600} \tag{3.51a}$$

3.5.2 Energy matrices

a. Thermal efficiency of system

It is determined by dividing the thermal energy output from system by the energy input to the system [86]:

$$\eta_{th} = \frac{\dot{m}\times L}{I_g A_R}\times 100 \tag{3.52}$$

b. Energy production factor (EPF)

System performance is predicted by EPF. It is calculated as the energy produced over the course of a life divided by the system's embodied energy [86].

$$EPF = \frac{E_{en,o}\times n}{E_{emb}} \tag{3.53}$$

c. Life cycle conversion efficiency (LCCE)

LCCE is the ratio of net energy productivity to energy input throughout life of system and is determined as [85,86]:

$$\eta_{LCCE} = \frac{(E_{en,o}\times n - E_{emb})}{(I_g A_R)\times n} \tag{3.54}$$

3.5.2 Carbon trading

Unlike, conventional (biomass based) steam distillation system, SSDS does not pollute the environment. Environmental analysis is performed based on the rate of CO_2 emission to environment in this study. The use of solar distillation systems minimises carbon emissions, which are a significant environmental issue. Around 0.98 kg CO_2/kW h of CO_2 is released into the environment on average when coal is used to generate electricity in a power station. However, this amount becomes 1.58 kg CO_2/kWh when distribution losses of 20% and transmission losses of 40% caused by inefficient electrical equipment are taken into account [85,87]. Eq. (24) can therefore be used to determine CO_2 emissions per year [86,88,89].

$$\mathrm{CO_2\,emissions\ per\ year\ (kg)} = \frac{\mathrm{E_{emb}}\times 1.58}{\mathrm{n}} \tag{3.55}$$

$$CO_2 \text{emissions(tons) over life span} = \frac{E_{emb} \times 1.58}{1000} \quad (3.56)$$

Reduction in carbon emissions to atmosphere is known as carbon mitigation. CO_2 mitigation per year can be estimated as [83]:

$$CO_2 mitigation\ per\ year\ (kg) = E_{en,o} \times 1.58 \quad (3.57)$$

Eq. (3.57) can be modified as Eq. (3.58) to calculate CO_2 mitigation for life span of system

$$CO_2 mitigationfor\ life\ span\ (tons) = \frac{E_{en,o} \times 1.58 \times n}{1000} \quad (3.58)$$

Net carbon dioxide (CO_2) mitigations over the lifetime (tons) can be estimated as:

$$\text{Net } CO_2 \text{mitigation for life span (tons)} = \frac{(E_{en,o} \times n - E_{emb})}{1000} \times 1.58 \quad (3.59)$$

Carbon credit is the amount given for preventing the emission of 1 ton of CO_2 into the atmosphere or for removing 1 ton of CO_2 from the atmosphere. The carbon credit for the proposed distillation system is calculated as [83]:

$$\text{Total carbon credit earned} = \text{Net } CO_2 \text{ mitigation} \times \text{carbon credit cost} \quad (3.60)$$

3.5.3 Environmental Parameters

CO_2 mitigated over life span (tons) from system is known as environmental parameters. Environmental parameters are calculated based on energy and exergy approach. Therefore, CO_2 mitigated over life span (tons) from system based on energy approach is calculated as [82,90]:

$$\emptyset_{en,CO_2} = \frac{E_{en,o} \times 1.58 \times n}{1000} \quad (3.61)$$

CO_2 mitigated over life span (tons) from system based on exergy approach is known as exergoenvironmental parameter and is calculated as [82,90]:

$$\emptyset_{ex,CO_2} = \frac{E_{ex,o} \times 1.58 \times n}{1000} \quad (3.62)$$

3.6 ENVIROECONOMIC ANALYSIS

The annual revenue from CO_2 mitigations over the course of system's lifetime is determined by the enviroeconomic approach. Energoenviroeconomic parameter is an approach that estimates revenue from CO_2 mitigation by considering energy values and can be expressed as [81,82,91] :

$$Z_{en,CO_2} = z_{CO_2} \times \emptyset_{en,CO_2} \tag{3.63}$$

A method for estimating CO_2 mitigation income by taking into account exergetic value is the exergoenviroeconomic parameter and is represented as [81,82]:

$$Z_{ex,CO_2} = z_{CO_2} \times \emptyset_{ex,CO_2} \tag{3.64}$$

The next chapter contains the results and discussion for both the proposed systems (CSD system and SSDS). It comprises the evaluation of yields, efficiencies of the system, energy and mass balance, extraction time, energy matrices, economic and environmental analysis of CSD system. Moreover, process parameters of CSD system are optimized using response surface methodology (RSM) and performance parameters are compared with previous studies. Further, it comprises the evaluation of energy distribution at different parts, energy and exergy efficiency, thermal losses various economic analyses (economic, exergoeconomic, and enviroeconomic), and the evaluation of pollutants emission-mitigations, and environmental cost (i.e., carbon credit values in the international market) of the proposed SSDS. Moreover, a comparative study of SSDS is being presented for peppermint and eucalyptus essential oil extraction.

CHAPTER: 4

RESULTS AND DISCUSSION

CHAPTER 4
RESULTS AND DISCUSSION

4.1 CONVENTIONAL DISTILLATION SYSTEM

Performance, mass and energy balance conducted over the process units of pilot plant, optimization of process parameters using RSM, detailed economic and environmental analysis of conventional steam distillation system were discussed in this section. Similar to this, overall extraction time for complete batch process including time for induction, loading and unloading of leaves and actual extraction was also presented and discussed. These results will be helpful for potential investors to get knowledge about number of batches to run per day, energy requirement and actual steam per batch, and stoppage time for extraction process.

4.1.1 Performance Evaluation

a. Thermal Performance of Conventional Distillation System

Thermal efficiency of the conventional distillation system is evaluated from Eq. (3.3). Hourly thermal efficiency for various batch sizes of Peppermint plants for three different days is illustrated in Fig. 4.1. Thermal efficiency was more for higher batch sizes due to more yield for higher batch sizes. Maximum thermal efficiency was obtained at 300 minutes of extraction time and 1900 kg batch size.

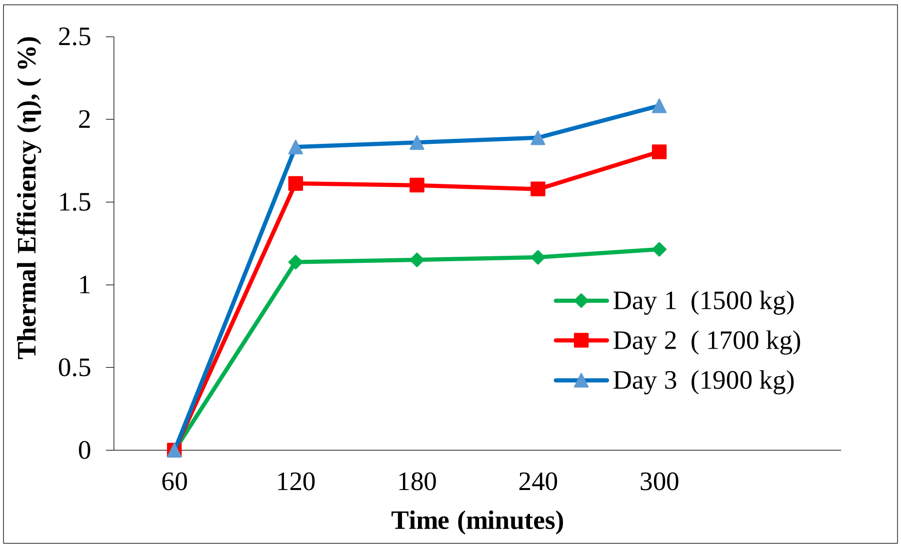


Fig.4.1 Variation in thermal efficiency with extraction time for different batch size

b. Operational Performance of Conventional Distillation System

Operational performance of the conventional distillation system is evaluated by measuring the system's productivity, EOY, extraction efficiency. Hourly productivity of the unit at different batch sizes of Peppermint plants for three different days is illustrated in Fig.4.2.

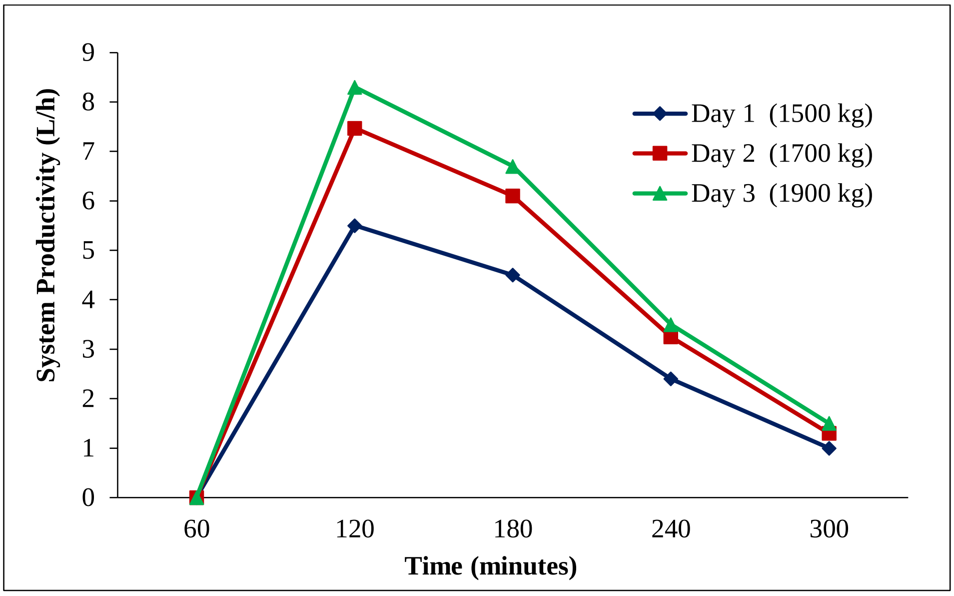


Fig.4.2 Hourly productivity of system with extraction time at various batch sizes

Fig.4.2 indicates that the maximum hourly productivity of the system is 8.3L/h at the time interval of 4-5 pm for the batch size of 1900 kg. It increases for the first two-hour interval in the initial and then decreases simultaneously. Hourly system productivity increases from 5.5 to 8.3 L/h with the increase in batch size from 1500 kg to 1900 kg during 4-5 pm. Hourly system productivity increased with the increase in plant batch size because generated steam increased in a distillation still. This generated steam accelerated the steam motion within the distillery, due to which volatile oil is extracted easily.

Cumulative productivity of the system at different batch sizes of plants for different time intervals is shown in Fig.4.3. It increases simultaneously with an increase in time and batch sizes of plant. Maximum cumulative productivity of the system is 20 L/h for 1900 kg plant batch size. It increases from 13.4 L/h to 20 L/h with an increase in batch size from 1500 kg to 1900 kg during 7-8 pm. Extraction efficiency of the system for different batch sizes is shown in Fig.4.4.

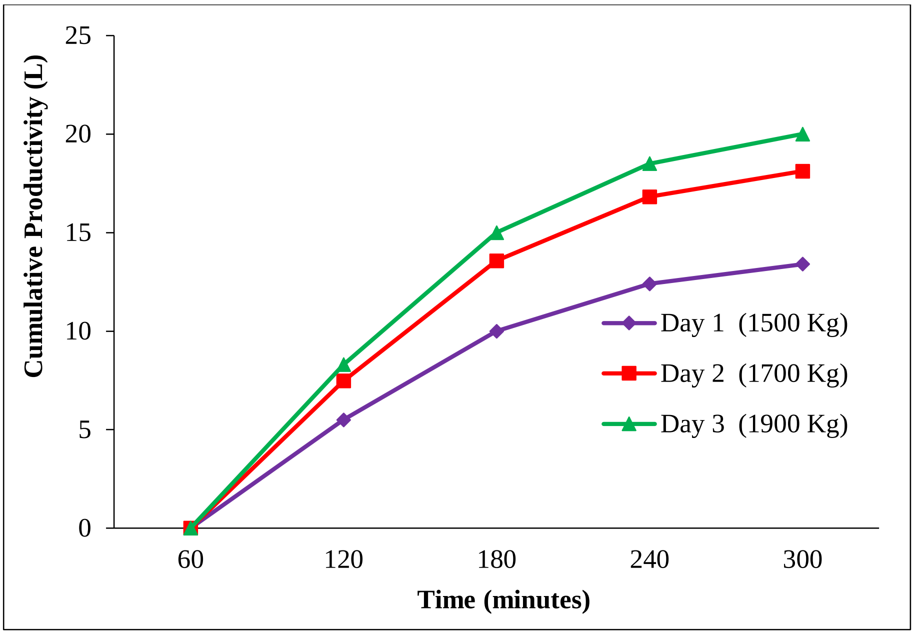


Fig.4.3 Cumulative productivity of system with extraction time at different batch sizes

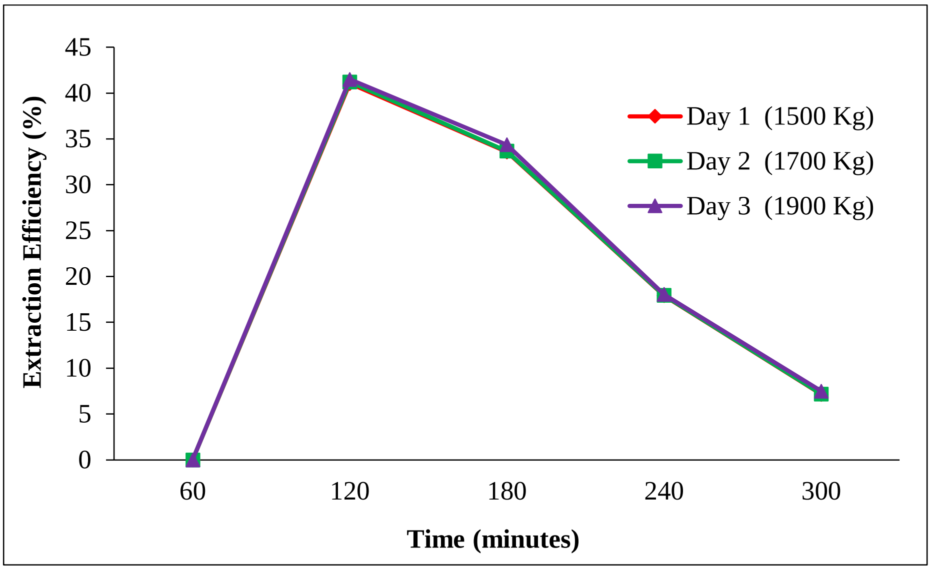


Fig.4.4 Variation in extraction efficiency of the system with extraction time

Experimental results show that the extraction efficiency of the system is increasing with the increase in batch sizes of plants. It increases for the first two hours of intervals and then decreases simultaneously with time. Maximum extraction efficiency is 41.5% for 1900kg batch size at the time interval of 4:00-5:00 pm. Extraction efficiency increases from 41.04 to 41.5% for batch size from 1500 kg to 1900 kg. There is a slight difference in the value of extraction efficiency due to a minor change in the batch size values. Therefore, the values of extraction efficiencies coincide in Fig.4.4. Average increase in extraction efficiency is 1.12%, with an increase in batch size from 1500 to 1900 kg at 4-5 pm.

Fig.4.5 illustrates the EOY of the system for different batch sizes of the plant at various time intervals. EOY increases with an increase in the batch size of the plant; however, all curves' trends are similar for all batches. Maximum EOY is 0.461% for the batch size of 1900 kg. EOY increases by 26% with the increase in batch size from 1500 to 1900 kg at 4-5 pm. EOY increases due to a steam rise generated, enabling volatile oil extraction by the rising batch size. Maximum EOY is obtained at 04:00-05:00 pm because maximum amounts of volatile oil are extracted at that time.

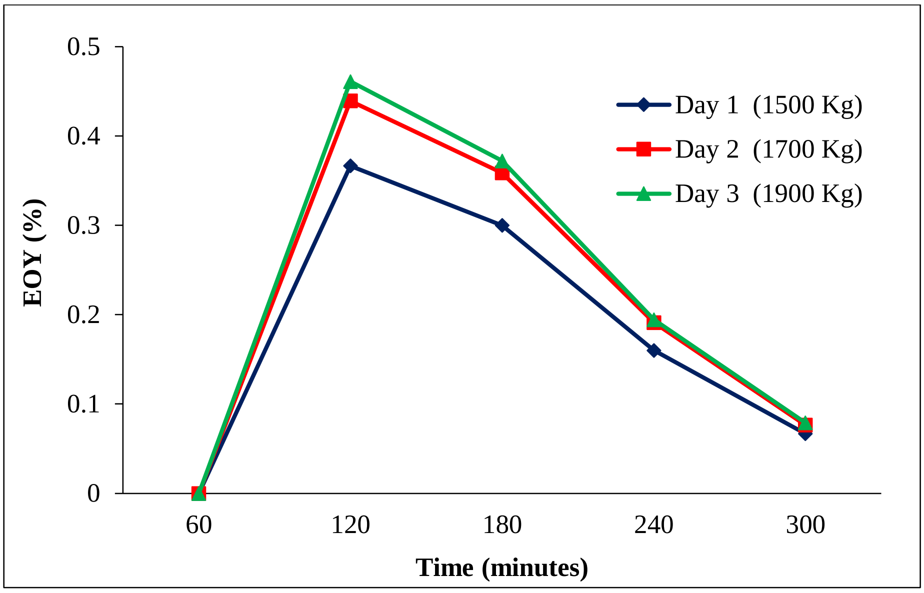


Fig.4.5 Variation in essential oil yield of system with extraction time

Overall performance of conventional steam distillation system to extract Peppermint oil is compared with previous research work and found that essential oil yield and extraction efficiency were 0.797% and 88.57% [30], 0.785% and 98.13% [15], 0.40% [28], respectively. In the present study, essential oil yield and extraction efficiencies were 0.461% and 41.5%. The comparison shows that results obtained in the present study are not much lower than those obtained in previous research on Peppermint oil extraction.

Performance parameters of present and previous studies are given in Table. 4.1. Peppermint oil extraction units in India are still based on old technology. These systems need attention to improve the design. Present study is performed at large-scale level and already published studies were performed at small-scale level. Hence, productivity is higher compared to previously published studies. Extraction efficiency and essential oil yield of published work are higher than in the present study because distillery was not insulated; therefore, losses are more. There is still a need to improve the design of Peppermint oil extraction unit in Indian area.

Table 4.1 Comparison of performance parameters of present study with previous research

Productivity (ml)	**Essential oil yield (%)**	**Extraction efficiency (%)**	**System efficiency (%)**	**References**
6.2	0.797	88.57	-	[30]
7.3	0.785	98.13	60.25	[15]
28.20	-	-	33.21	[29]
-	0.40	-	-	[28]
1	3.7	-	-	[31]
39	-	-	-	[92]
20000	0.461	41.5	-	Present study

4.1.2 Optimization using Response Surface Methodology (RSM)

RSM was utilized to optimize process parameters that affect the essential oil yield. Two process parameters were selected: extraction time A (60, 180 and 300 min) and batch size B (1500,1700 and 1900 kg) to obtain the maximum essential oil yield from peppermint leaves. Prior experiments determined the range for every independent variable. Every parameter was examined at three levels: lower (-1), higher (+1), and central values (0), as shown in Table 4.2. The experimental data was designed using a design expert software 11.0 with face-centered central composite design (CCD). This created 13 trials to determine the pure error. The extraction yield (%) was chosen as the response (dependent variable). Table 4.2 shows the independent variables considered for optimization. Table 4.3 shows the various operating parameters of the experiments conducted in CCD.

Table 4.2 Experiments range and levels of input parameters for optimization

Extraction parameters	Units	Symbol	Coded Levels		
			Lower level (-1)	Central value(0)	Higher Level (1)
Extraction Time	min	A	60	180	300
Batch sizes	kg	B	1500	1700	1900

Table 4.3 No. of runs of CCD

	Factor 1	Factor 2	Response 1
Run	A:Extraction Time	B:Batch Size	Yield
	min	kg	%
1	180 (0)	1700 (0)	0.79
2	60 (-1)	1700 (0)	0.1
3	180 (0)	1700 (0)	0.8
4	300 (1)	1700 (0)	1.06
5	300 (1)	1500 (-1)	0.89
6	300 (1)	1900 (1)	1.05
7	180 (0)	1500 (-1)	0.66
8	180 (0)	1700 (0)	0.81
9	60 (-1)	1900 (1)	0.2
10	180 (0)	1700 (0)	0.78
11	60 (-1)	1500 (-1)	0
12	180 (0)	1700 (0)	0.82

13	180 (0)	1900 (1)	0.78

Response achieved for every run of CCD, coded experiments, influence of ET and batch size on extraction yield were investigated. Table 4.3 represents experimental oil yield (%) under various permutations of extraction conditions. The highest and lowest essential oil yield was found in experiment number 4 and 11, respectively.

a. Fitting the model

RSM was utilized to obtain the optimal condition of process parameters to achieve the maximum peppermint oil yield. A quadratic polynomial equation was used for fitting the observed data of analyzed variables. The response surface analysis used a generalized second-order polynomial model, which is written as:

$$Y = 0.7952 + 0.45A + 0.08B - 0.01AB - 0.2031A^2 - 0.0631B^2 \quad (4.1)$$

Where Y is the extraction yield (response) and, A and B are independent variables. The number of CCD runs performed in this study is shown in Table 4.3.

b. ANOVA for the model

Table 4.4 shows the ANOVA of the resultant polynomial model of the observational data. P-values ($P<0.05$) indicate that model is significant. Model F-value is 22.56, indicating that the model is statistically significant and there is only a 0.01 % chance that F- Value could occur due to noise. The Terms A, B, A^2 and B^2 are significant ($P<0.1$) in this situation. The model term AB is not relevant ($P>0.1$). The lack of Fit F-value of 6.3 indicates that the lack of fit is not considerable. Results of present study indicate that coefficient of determination (R^2) was 0.9960 for the regressive model. This indicates that independent variables are responsible for 99.56% of sample variation and only 0.44% of total variation is not explained by this model. A high R^2 shows that the data can adequately account for the variation to fit the model. The predicted model appeared to be a good fit for the observed data. As a result, the model adequately explained the response. Model's accuracy is not implied by considering only R^2 because adding a variable in model increases the R^2. Therefore, Adj-R^2 is better to evaluate the model if R^2 value is greater than 90% [93]. In this study, both R^2 (0.9960) and Adjusted R^2 (0.9931) indicated that quadartic regression model suited the response values well and that the observed and predicted values are consistent. Model is acceptable since the predicted R^2 of 0.9673 is in reasonable agreement with the Adjusted R^2 of 0.9931 i.e. the difference is less than 0.2 (Table 4.5). Signal to noise ratio is measured by "Adeq Precision". "Adeq Precision" of 54.464 (>4) implies that model is acceptable and used to explore the design space. Coefficient of variation (CV)<10 suggested that the model is reproducible [93]. CV of 4.26 values implies that experimental data is reliable and model is repeatable.

Table 4.4 ANOVA for polynomial model

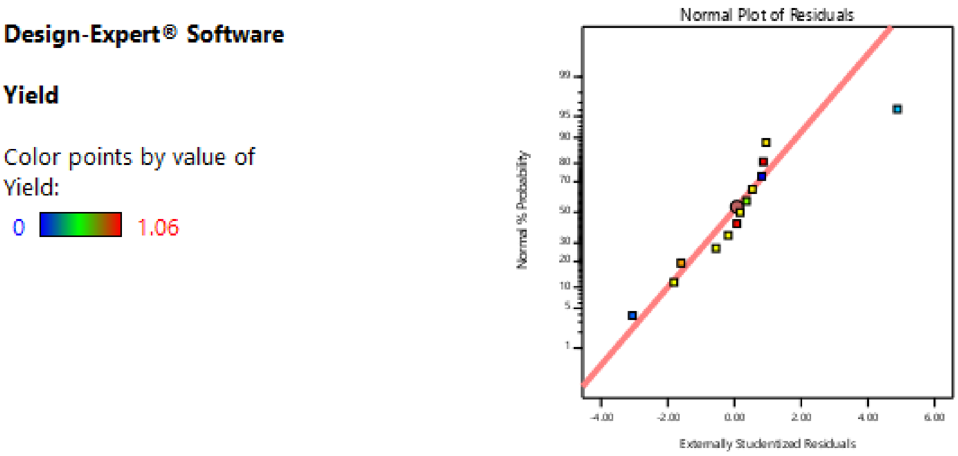
Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.43	5	0.2863	348.85	< 0.0001	significant
A-Extraction Time	1.21	1	1.21	1480.46	< 0.0001	
B-Batch Size	0.0384	1	0.0384	46.79	0.0002	
AB	0.0004	1	0.0004	0.4874	0.5076	
A^2	0.1139	1	0.1139	138.82	< 0.0001	
B^2	0.0110	1	0.0110	13.40	0.0081	
Residual	0.0057	7	0.0008			
Lack of Fit	0.0047	3	0.0016	6.33	0.0534	not significant
Pure Error	0.0010	4	0.0002			
Cor Total	1.44	12				

Table 4.5 Fit statistic

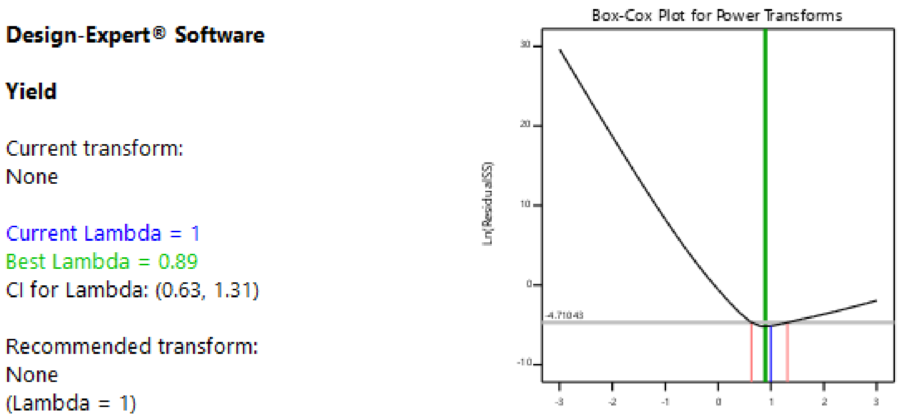
Std. Dev.	0.0286	**R^2**	0.9960
Mean	0.6723	**Adjusted R^2**	0.9931

C.V. %	4.26	**Predicted R^2**	0.9673
		Adeq Precision	54.4644

Studentized residuals vs. probability curve is shown in Fig.4.6(a). Figure illustrates that data is spread over a line and indicates that residuals follow a normal distribution. Fig.4.6(b) illustrates the Box-Cox curve for power transform. The plot shows best lambda 0.89 with lower and higher confidence intervals as 0.61 and 1.31, respectively. Distribution of studentized residuals against run number and predicted yield of peppermint oil is illustrated in Fig.4.7. Studentized residuals follow a random pattern with respect to run numbers.

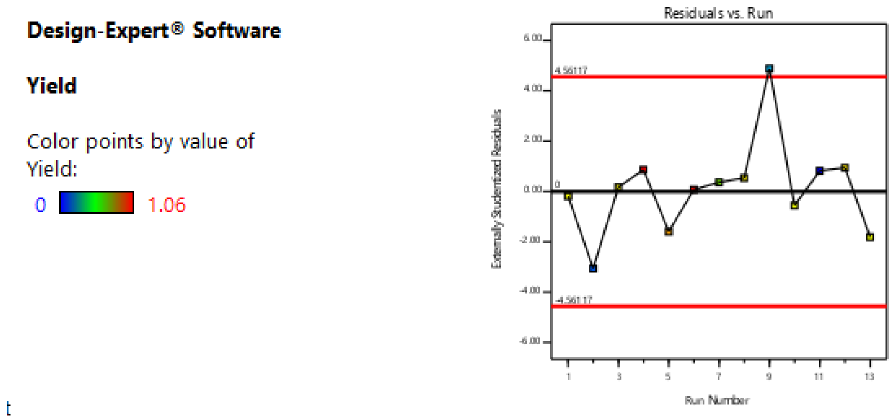


(a)

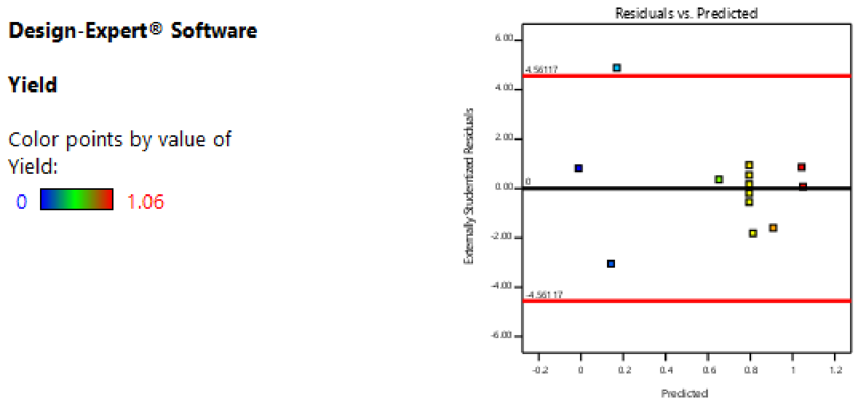


(b)

Fig.4.6 (a) Normal plot of residuals (b) Box-Cox plot for power transform



(a)



(b)

Fig.4.7 Studentized residuals vs. (a) Run number (b) predicted response for yield of peppermint oil

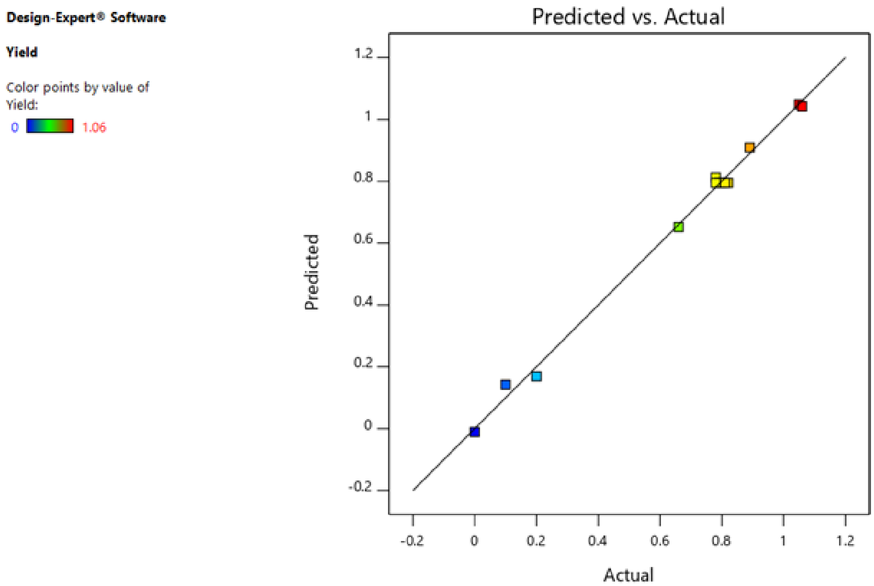
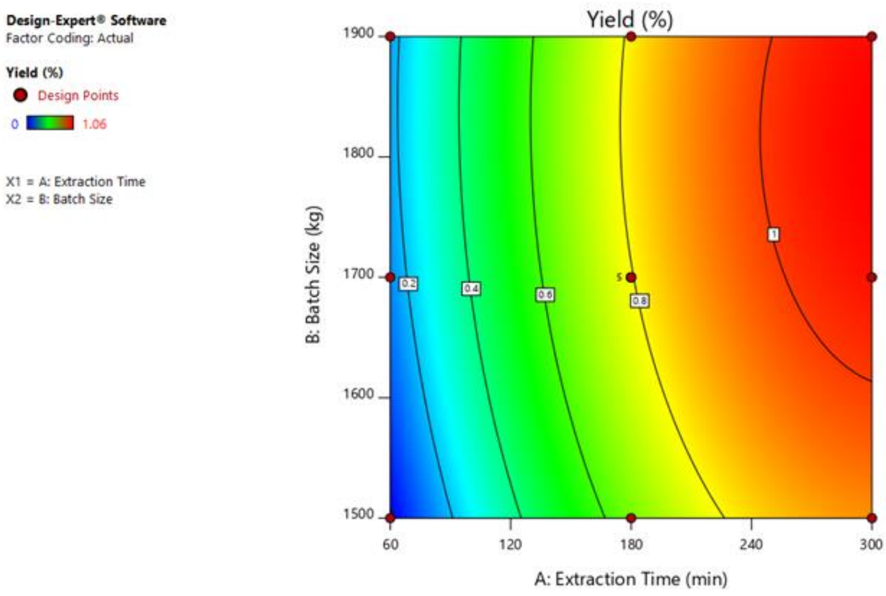


Fig.4.8 Actual and predicted values for yield

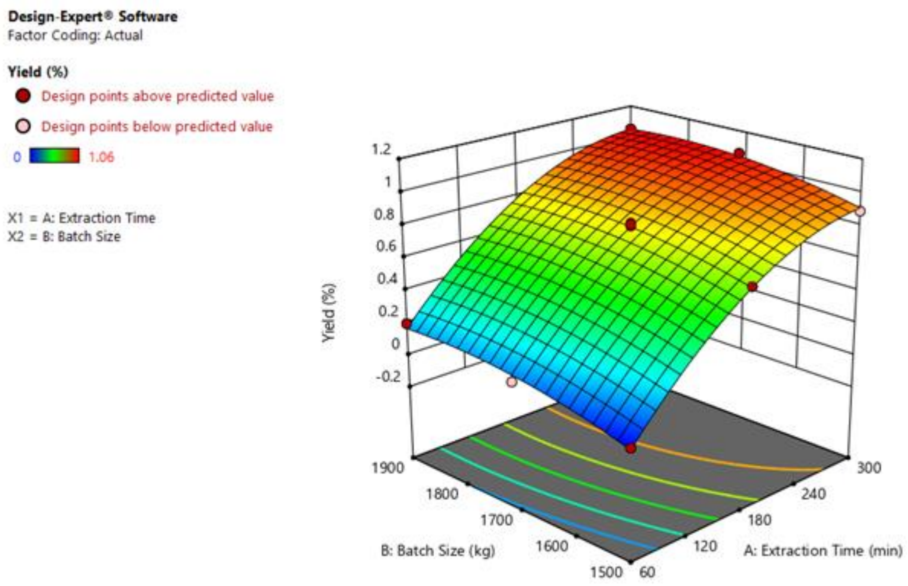
Fig.4.8 represents the relationship between actual and predicted values for peppermint oil yield. Predicted values are scattered close to the 45˚ line, indicating the polynomial model's good predictive accuracy. The actual and predicted yield values lie equally on both sides of the line.

c. Contour and response surface plots

Response surface and contour plots clearly illustrate the relationship between dependent and independent variables. 2D Contour plots and 3D response surface plots are used to depict the interactive effects of process parameters on extraction yield. Furthermore, the plots are used to estimate the maximum yield. One parameter remains constant at central value while the other two vary [94]. In this study, the combined effect of ET and batch size on extraction yield of peppermint oil is shown in Fig.4.9(a) and Fig.4.9(b). This study indicates that extraction yield increases with increase in batch size and ET, but increasing ET shows a larger effect on yield than batch size. The contour plot shows that the oil yield could reach approximately 1.06% when ET ranges from 238 to 300 min and batch size from 1600 to 1900 kg.



(a)

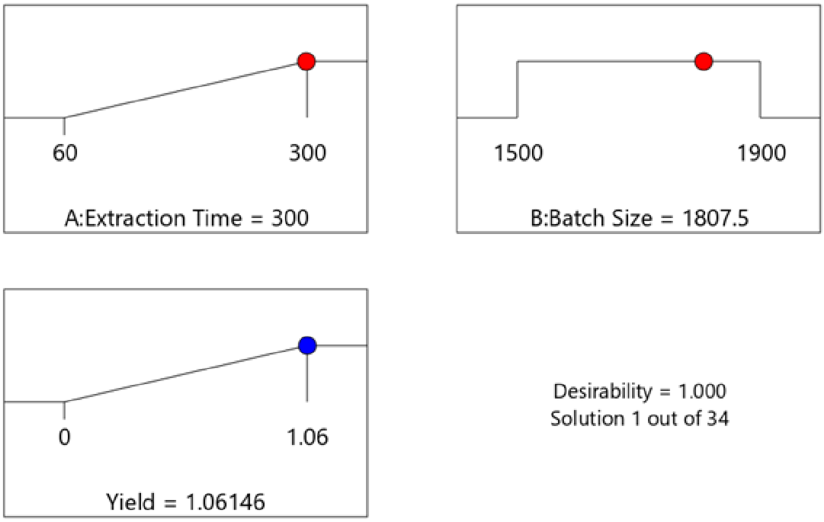


(b)

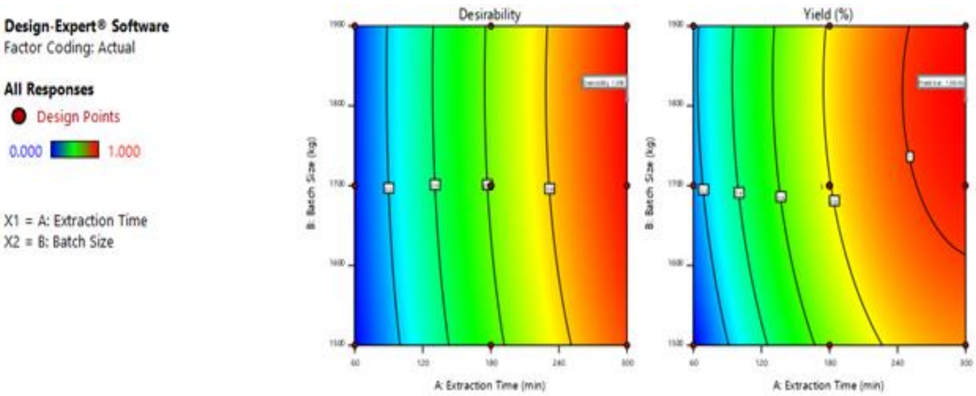
Fig.4.9 Contour and response surface plot (a) 2D (b) 3D

d. Optimal condition

Out of 34 solutions generated by software, one is selected as an optimal solution at maximum oil yield. Red-colored points show the optimal conditions (ET and batch size) and the maximum peppermint oil yield shown by blue cloured dot in Fig.4.10(a). Desirability of solution is 1 as shown in Fig.4.10(b). This indicates that these conditions are the best optimal solutions for present study. As per the results of RSM, the maximum yield of 1.06% was obtained at 300 min ET and 1807.5 kg batch size of peppermint plants. Experiments were further performed for 1807.5 kg and yield was found as 1.04%. Predicted value of yield was obtained as 1.06%. Experimental and predicted yield values are in good consistency with percentage deviation of 1.436.



(a)



(b)

Fig.4.10 (a) Optimal conditions (b) Contour plot of desirability of solutions

4.1.3 Mass balance

Table.4.6 summaries the mass balance conducted at different operational unit of plant. It is obvious that 1.111×10^{-3} kg/s of essential oil were produced by charging every 1.05×10^{-1} kg/s of peppermint leaves into extracting unit and requirement of steam was 3.29×10^{-2} kg/s. This suggests that steam to leaves ratio and oil to leaves ratio was 1: 3.2 and 1: 94.5, respectively.

Table 4.6 Summary of mass balance for operational units

S. No.	Operational Units	Mass In (kg/s)	Mass out (kg/s)
1	**Extracting Unit**		
	Peppermint Leaves	1.05×10^{-1}	
	Water	5.55×10^{-2}	
	Steam		3.29×10^{-2}
	Oil		1.111×10^{-3}
	Spent Leaves		9.91×10^{-2}
	Unused Water		$2.26x\ 10^{-2}$
	Total	$\mathbf{1.605 \times 10^{-1}}$	$\mathbf{1.605 \times 10^{-1}}$
2	**Condenser**		
	Steam	3.29×10^{-2}	
	Essential Oil	1.111×10^{-3}	1.111×10^{-3}
	Cooling Water	6.302×10^{-3}	
	Hot Water		3.29×10^{-2}
	Warm water		6.302×10^{-3}
	Total	$\mathbf{1.07 \times 10^{-1}}$	$\mathbf{1.07 \times 10^{-1}}$
3	**Florentine Flask**		
	Hot water	3.29×10^{-2}	$3.22\ x\ 10^{-2}$
	Essential oil	1.111×10^{-3}	1.811×10^{-3}
	Total	$\mathbf{3.401 \times 10^{-2}}$	$\mathbf{3.401 \times 10^{-2}}$

4.1.4 Energy balance

Table 4.7 summarizes the energy balance conducted over operational units of pilot plant. At a steady state condition, the total energy supplied (267316.5 J/s) is equal to energy gained by water (17482.5 J/s), peppermint leaves (2819.25 J/s), essential oil (0.08325 J/s), extraction tank (89892.61 J/s), and energy lost to environment (82768.05 J/s) and due to evaporation (74354 J/s). However, energy acquired by oil (8.325 x 10^{-2} J/s) was negligible compared to water (17482.5 J/s) and leaves (2819.25 J/s). Since temperature in Florentine flask was constant (25 °C), there was no energy change.

4.1.5 Energy requirement

Energy and fuel consumption per batch size is depicted in Fig.4.11. Maximum energy and fuel consumption were 4966.08 MJ and 193 kg, respectively for 1500 kg batch size due to sensible and latent heat addition. Energy and fuel consumption for other two batches are lower than that of 1500 kg batch size due to only latent heat addition. Minimum energy and fuel consumption were required for 1900 kg batch size. Results concluded that energy and fuel consumption were higher for first batch size and then decreased simultaneously for next batch size.

Table 4.7 Energy balance for different units of pilot plant

S. No.	Operational Units	Energy In (J/s)	Energy out (J/s)
1	**Extracting Unit**		
	Heat supplied	267316.5	
	Heat gained by water		17482.5
	Heat gained by leaves		2819.25
	Heat lost to environment		82768.05
	Heat gained by Oil		0.08325
	Heat due to evaporation		74354
	Heat gained by extraction tank		89892.61
	Total	**267316.5**	**267316.5**
2	**Condenser**		
	Energy released by steam	74354	
	Energy released by Oil	0.08325	
	Energy gained by cooling Water		74354.08
	Total	**74354.08**	**74354.08**

3	**Florentine Flask**		
	Hot water	13788.39	13788.39
	Essential oil	0.721	0.721
	Total	**13789.11**	**13789.11**

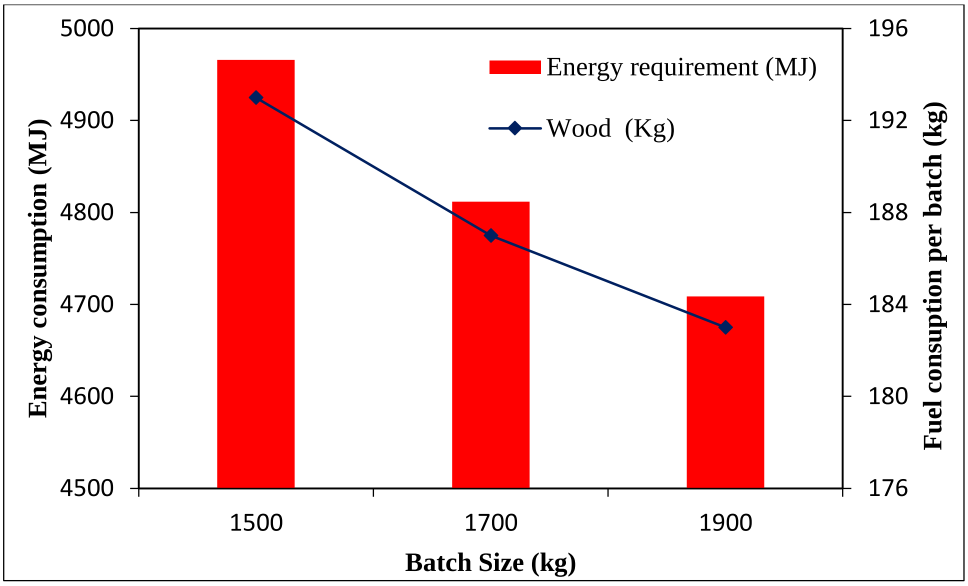


Fig.4.11 Energy and fuel consumption per batch

4.1.6 Total Extraction time

Table 4.8 shows that total average production time per batch for a production cycle was 442.3 minutes including time required to load the peppermint leaves into extracting unit (23 minutes), induction time (80 minutes), actual extraction time (300 minutes), and time required to off-load the spent leaves (40 minutes). Average lag time (T_1+ T_4) of production cycle was 62.3 minutes.

Table 4.8 Total extraction time per batch size in a production cycle

Batch size (kg)	Loading of fresh peppermint leaves (T_1), minutes	Induction time (T_2), minutes	Actual extraction time (T_3), minutes	Off-loading of spent leaves (T_4), minutes	Total production time (Te), minutes
1500	20	85	300	35	440
1700	22	75	300	40	437

1900	25	80	300	45	450
Average	22.3	80	300	40	442.3

The induction period is interval of time between start of fuel ignition and first drop of steam-oil mixture. This duration mainly depends on the amount of water in boiler, energy supply and leave's loading density. Induction time for batch size (1500 kg) was higher than other two batches because fresh water in boiler received both sensible and latent heat additions, whereas in the other two batches only latent heat was added.

4.1.7 Detailed economic analysis

a. Total investment

Table 4.9 and Table 4.10 show various costs associated to establish a pilot plant for essential oil extraction from peppermint leaves producing 80 liters of essential oil per day for a potential investor. The Major equipment's such as boiler, distillery, and condenser were estimated to cost US$3,344.86. However, cost of piping, instrumentation, building and other non-depreciable items was estimated to US$1,647.48. Therefore, total direct cost of pilot plant was obtained as US$4992.34. Total indirect cost (Cost of design and construction) of system was estimated to US$2688.18. Hence, total initial investment needed to a potential investor for establishing a pilot plant of peppermint oil extraction by steam distillation extracting 24000 liters of essential oil per year (300 working days) amounted to 7680.53 US$ as shown in Fig.4.12.

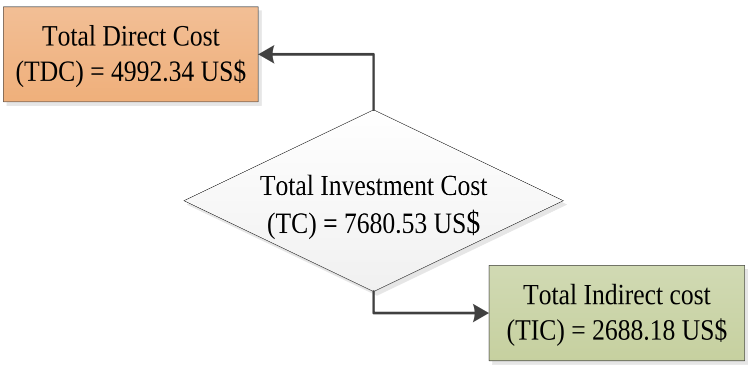


Fig.4.12 Total investment cost of system

b. Annual operating cost (AOC)

Annual operating cost (AOC) of system includes annual direct production cost, annual indirect production cost, cost of raw material, cost of fuel and cost of utilities, as shown in Fig.4.15. Labor cost amounting to US$18480 per year for eight unskilled labors at US$7.70/day per head. Annual maintenance cost (MC) and plant overhead cost (POC) were estimated at US$768.05 and US$768.05, respectively which are 10% of total initial investment. Considering 5% of total initial investment, local taxes (LT) and insurance (I) were US$384.02, respectively. Therefore, Annual direct production cost (ADPC) of system, including MC, POC, LT and I, amounts to US$20,784.14 as shown in Fig.4.13.

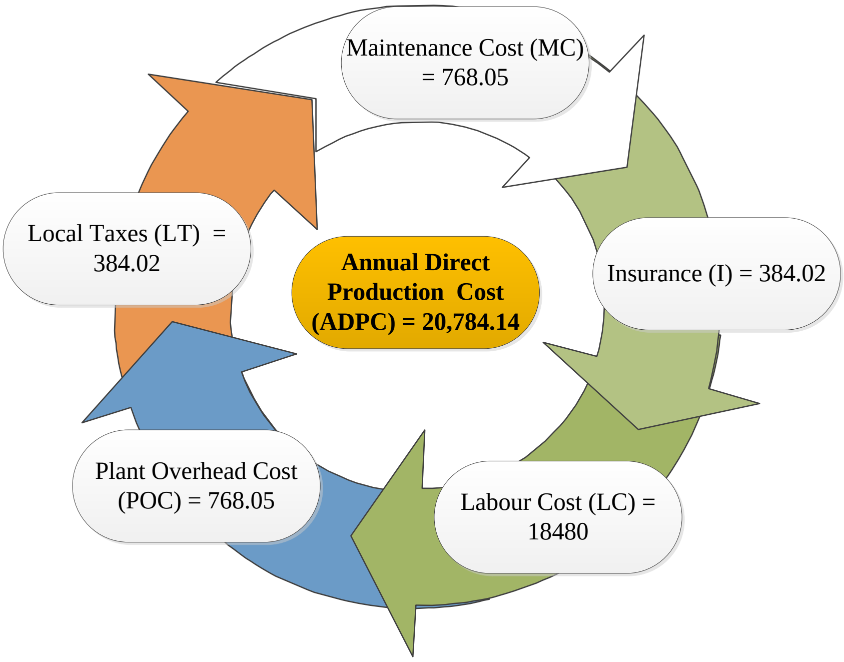


Fig.4.13 Annual direct production cost of system

Sales expenses (SE), general overhead (GO) and R&D were considered as 4%, 4% and 8% of ADPC and amounting to US$800.64, US$800.64 and US$1601.28, respectively. Therefore, Total annual indirect production cost (AIPC) of system including SE, GO and R&D was estimated at US$3202.56 as depicted in Fig.4.14.

Raw material (RM) used in distillation system was peppermint leaves with requirement of 2400000 kg/year, amounting to US$450,000 at US$0.18 per kg. Fuel used for producing thermal energy in furnace was mango wood and bought from local market at US$0.10 per kg. Fuel requirement was 100 kg per batch (400 kg per day). Therefore, fuel cost (FC) was estimated at US$12321.9 per year. Cost of utilities (UC) was considered as US$6299.57. Hence, AOC of system, including RM, FC, U, ADPC and AIPC to extract 24 kiloliters of peppermint oil was estimated at US$492,608.17 as depicted in Fig.4.15.

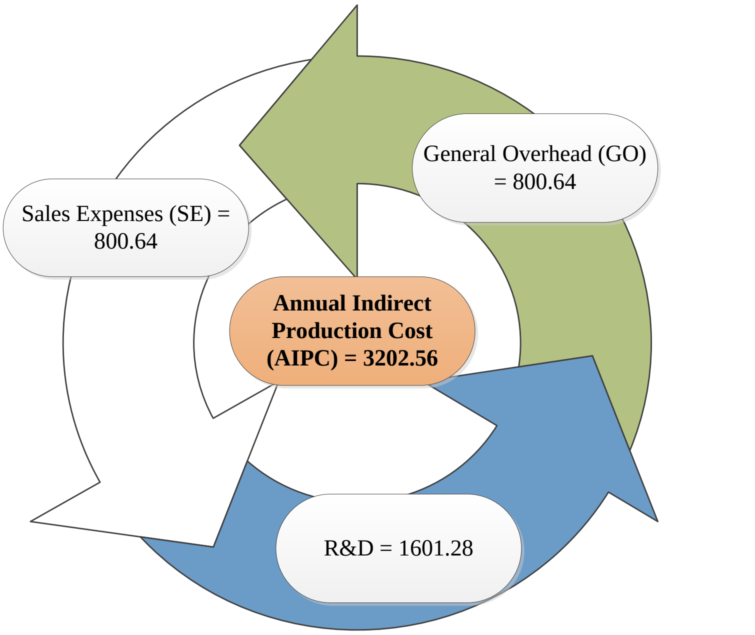


Fig.4.14 Annual indirect production cost of system

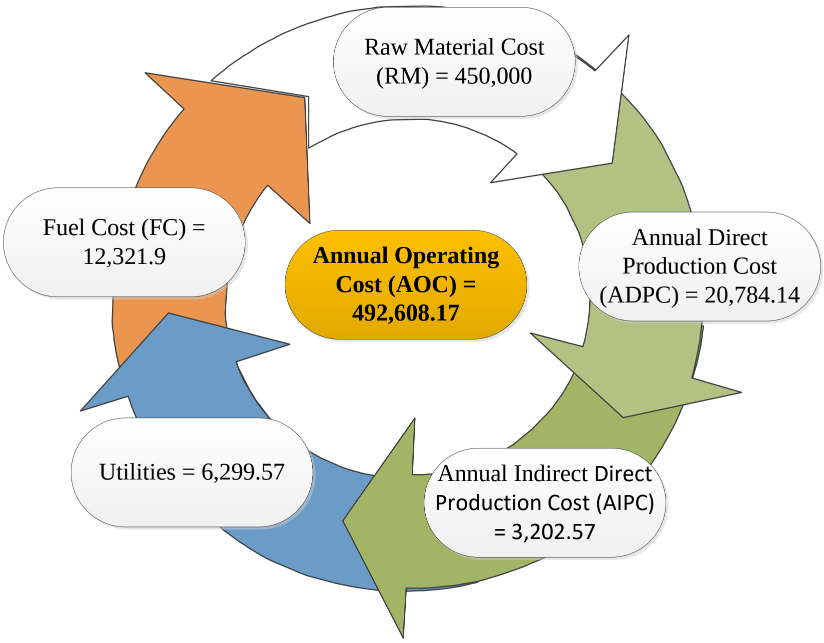


Fig.4.15 Annual operating cost of system

c. Cost analysis of profit

Annual production of essential oil from system was 24 kiloliters based on daily production of 80 liters in four batches for 24h of operation. The estimated selling price of essential oil was US$499920 per year at US$20.83 per liter. Annual estimated operational profit gained from system was US$7311.83, as depicted in Fig.4.16. Profit before tax (PBT) was estimated at US$6927.81 by considering annual depreciation of US$384.02 and life span of 18 years. Profit after tax (PAT) was gained as US$5680.81 at a tax rate of 18%. PAT is estimated to increase in successive years of operation by enhancing utilization capacity of system or optimizing operational parameters, including labor utilization.

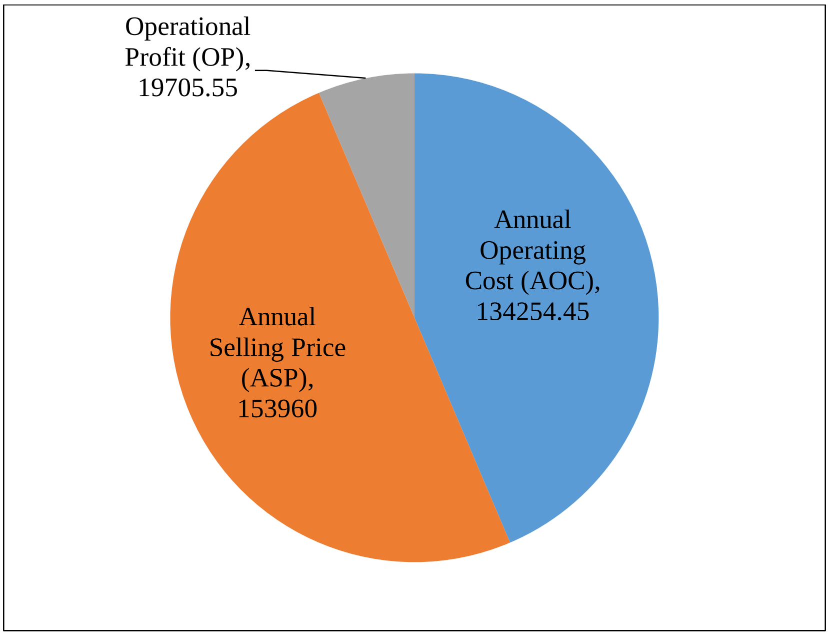


Fig.4.16 Operation profit of system (US$)

The estimated return on investment (ROI) was 73.96%, with a profit margin of 1.13% and return of equity at estimated value of equity of 20% of total investment was 1,536%. Internal rate of return was positive at 85.73% over the projected economic life span of 18 years. Annual cash flow and payback period (PBP) were US$6064.83 and 1.26 years, respectively. Table 4.10 illustrates summary of profit analysis.

Table 4.9 Summary of various cost associated to set up a pilot plant

Items	Equation	Value	Cost (US$)	Total Amount (US$)
Total direct cost of system (TDC)			4,992.3	
Total indirect cost of system (TIC)			2,688.2	
Total cost of system or Total investment cost (TC)	$\boldsymbol{TC = TDC + TIC}$			**7,680.5**
Raw Materials (RM), kg/year		2,400,000	4,50,000	
Fuel Cost (FC)			12,321.9	
Utilties (U)			6,299.6	
Maintenance cost (MC), 10% of TC			768.1	
Labour cost (LC)			18,480	
Plant overhead cost (POC), 10% of TC			768.05	
Local taxes (LT), 5% of TC			384.02	
Insurance (I), 5% of TC			384.02	
Annual direct production cost (ADPC)	$\boldsymbol{ADPC = MC + LC + POC + LT + I}$			**20,784.1**
Sales expenses (SE), 4% of ADPC			800.64	
General overhead (GO),			800.64	

(4% of ADPC)			
R&D (8% of ADPC)		1,601.3	
Annual indirect production cost (AIPC)	$\boldsymbol{AIPC = SE + GO + R\&D}$		**3,202.5**
Annual Operating Cost (AOC)	$\boldsymbol{AOC = RM + FC + U + ADPC + AIPC}$		**492,608.2**

Therefore, it was clear from profit cost analysis based on various estimations and assumptions made that pilot plant is expected to recover its initial cost (total investment of US$7680.53) in two years of operation (PBP of 1.26 years), with an expected income amounting to US$7311.83 in first year of operation.

Table 4.10 Summary of various cost associated with profit analysis

Items	Equation	Value	Cost (US$)	Total Amount (US$)
Annual production of essential oil (kiloliters)		24		
Annual selling price (ASP)		20.83($/L)		499,920
Operational profit (OP)	$\boldsymbol{OP = ASP - AOC}$			**7311.8**
Life of system (LS), Years		18		
Salvage value (SV)	$SV = 0.10 \times TC$		768.05	
Depreciation (D)	$D = (TC - SV)/LS$		384.02	
Profit before tax (PBT)	$PBT = OP - D$			6927.8
Tax (T)	$T = 0.18 \times PBT$	18%	1247	
Profit after tax (PAT)	$\boldsymbol{PAT = PBT - T}$			**5680.8**

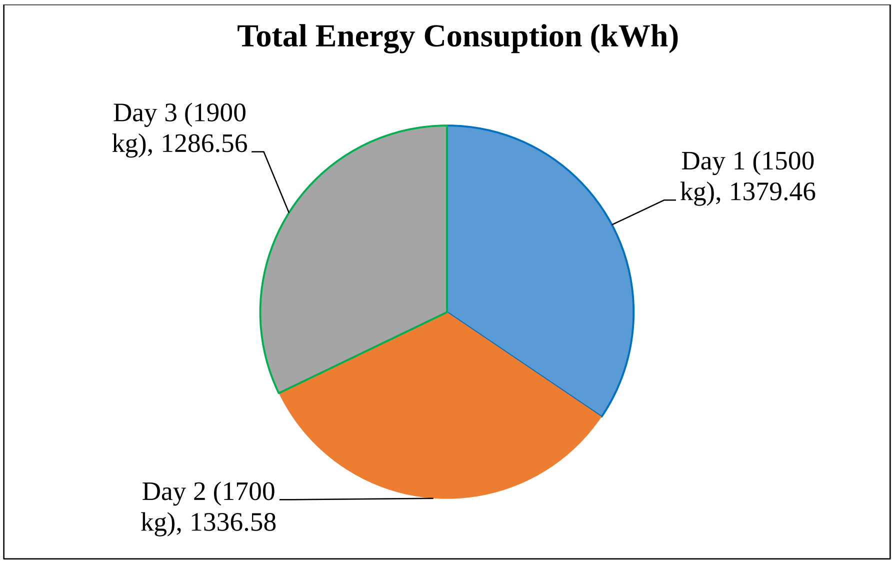
Return on investment (ROI), %	$ROI = (PAT/TC) \times 100$	**73.9**
Profit margin (PM), %	$PM = (PAT/ASP) \times 100$	1.13
Equity	@20%	
Return on equity (ROE), %	$ROE = 0.20 \times TC$	1536
Annual cash flow (ACF)	$ACF = PAT + D$	6064.8
Payback period (PBP), Years	$PBP = TC/ACF$	**1.26**
Breakeven point (BEP)	$BEP = TC/OP$	1.05
Internal rate of return (IRR), %		**85.7**

4.1.8 Environmental Impact

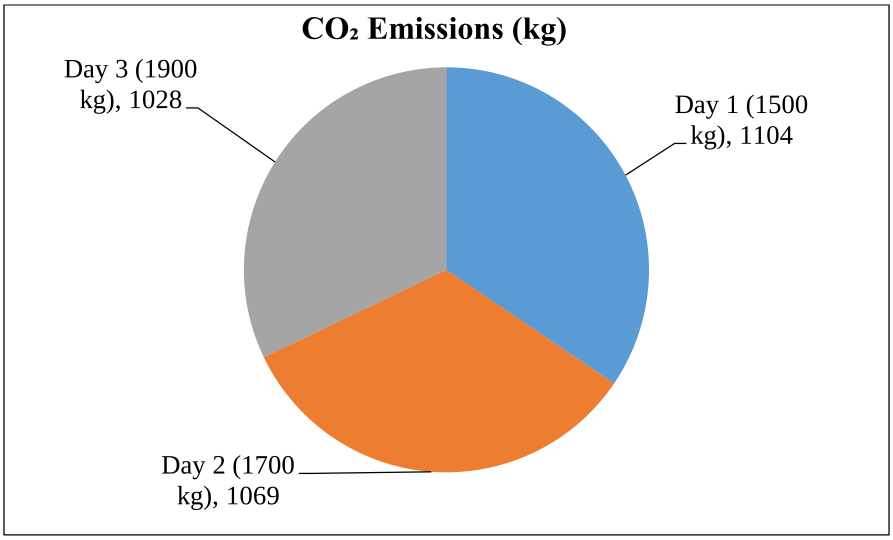
Environmental analysis of CSD system can be carried out by calculating CO_2 emissions: (i) by direct burning of biomass (ii) in terms of carbon trading, as CO_2 can be emitted from CSD system by direct burning of biomass and by materials during its fabrication.

4.1.8.1 CO_2 emissions by direct burning of biomass

Total energy consumption (TEC) and CO_2 emissions for one complete cycle of CSD system were calculated by Eq. (3.13) and (3.14), respectively, to assess the environmental impact. Different batch sizes (1500, 1700 and 1900 kg) were used to analyse the environmental impact of steam distillation system. TEC and CO_2 emissions for different batch sizes are depicted in Fig.4.17.



(a)



(b)

Fig.4.17 Environmental impact (a) Total energy consumption (b) CO_2 emissions

TEC and CO_2 emissions are decreasing with an increase in batch size, as shown in Fig.4.17. As TEC is decreasing with increase in batch size, therefore, CO_2 emissions are also decreasing. TEC for 1500, 1700 and 1900 kg batch sizes are 1379.46, 1336.58 and 1286.56 kWh, while CO_2 emissions are 1104, 1069 and 1028 kg, respectively.

4.1.8.2 Environment analysis in terms of carbon trading

a. Embodied energy of CSD

List of weight of various components and embodied energy of the various materials used to fabricate conventional distillation system (CSD) for peppermint oil extraction is shown in Table 4.11. CSD system is composed of several components, with a total weight of 10013.05 kg. Weight percentages of various materials are illustrated in Fig.4.18. Most of the weight percentages are occupied by extraction unit (distillery), which weighs 3173.36 kg (32%), followed by furnace, which weighs 2500 kg (25%), boiler, which weighs 2173.6 kg (22%), condenser which weighs 2020.6 kg (20%) and then by other materials like the connection pipe, water storage tank Florentine flask, gasket, etc.

Fig.4.19 illustrates detailed embodied energy shares of the various materials utilized to construct the CSD system. The developed system has a total embodied energy of 166237 kWh (598454 MJ). Mild steel, which accounts for around 98% of the total embodied energy, is used to construct the distillery, boiler condenser and supporting structures. The connection pipes, made of galvanized iron, contributed around 1% of the second largest amount of embodied energy. Due to its lack of energy requirements during production, furnace, gasket, Florentine flask and water storage tank have roughly 1% of embodied energy.

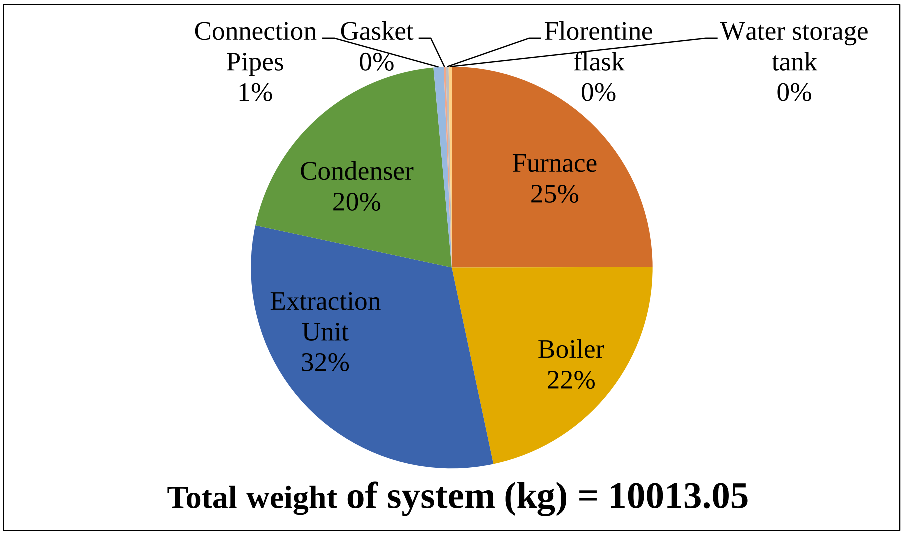


Fig.4.18 Weight of components of CSD

Table 4.11 Estimated embodied energy of CSD

Components of CSD	Material	Energy Intensity (MJ/kg)	Weight of Components (kg)	Embodied Energy (MJ)
Furnace	Blocks	2.5	2500	7125
	concrete	0.35		
Boiler	Steel	79	2173.6	171714.4
Extraction Unit	Steel	79	3172.36	250616.44
Condenser	Steel	79	2020.6	15627.4
Connection Pipes	Galvanized Iron	49	81.82	4009.18
Gasket	Rubber	130	15.6	2028
Florentine flask	Steel	49	23.07	1130.43
Water storage tank	PVC	85	25	2125
			Total	**598454**

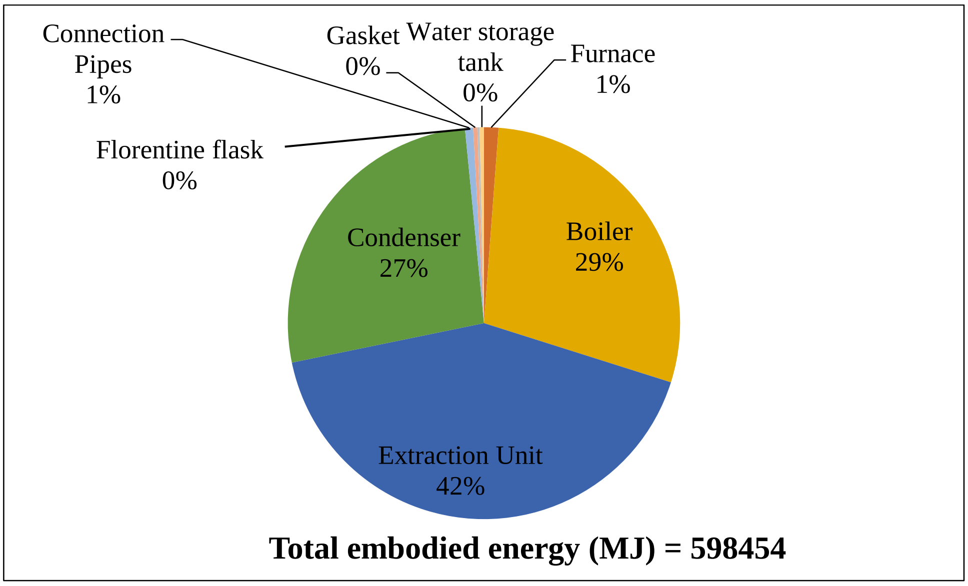


Fig.4.19 Embodied energy of CSD

b. Energy payback time (EPBT)

Energy payback time for CSD system was obtained as 0.61, 0.54 and 0.46 years for 1500, 1700 and 1900 kg batch size of peppermint, as shown in Fig.4.20. EPBT heavily depends on capacity of CSD system. If capacity (batch size) is exceeded, the EPBT will be further decreased. However, if peppermint plants increase, the rate at which oil is evaporated from plants may increase.

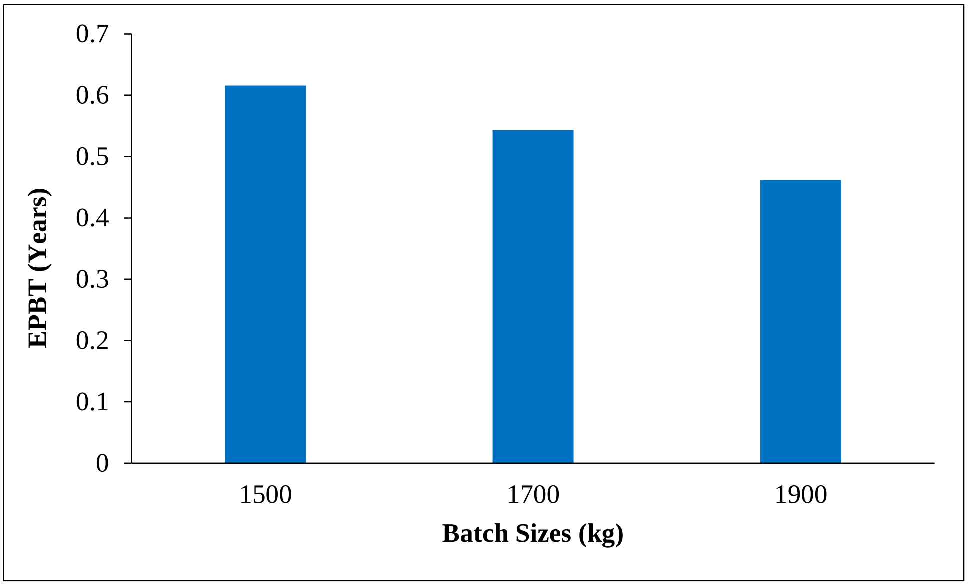


Fig.4.20 Energy payback time for CSD

c. Energy Matrices

Thermal efficiency increases with the increase in plant batch size (Fig.4.21). It varies from 0 to 1.214%, 0 to 1.804%, and from 0 to 2.081% for 1500 kg, 1700 kg, and 1900 kg batch size. Trend for all curves is similar for all batch sizes. Maximum thermal efficiency was 2.0% for 1900 kg batch size at the period of 7-8 pm. Hence, it increases due to an increase in the system's yield and reduced fuel consumption per hour.

The estimated values of thermal efficiency, EPF and LCCE are shown in Table 4.12. EPF, a dimensionless quantity, represents the overall impact of losses on the rated output. Total thermal energy output from distillation unit is estimated to be 270000 kWh, 306000 kWh and 360000 kWh for 1500, 1700 and 1900 kg batch size, respectively by taking into account the conversion of energy of wood fuel into equivalent thermal energy.

Thermal efficiency, EPF and LCCE increase with increase in batch size as shown in Fig.4.21 and Fig.4.22. Maximum thermal efficiency was obtained as 1.06% for 1900 kg batch size. Lower value thermal efficiency of CSD system was obtained due to various losses in furnace and non-insulated distillery. Annual EPFs are estimated to be 1.62, 1.84 and 2.16 for 1500, 1700 and 1900 kg batch sizes of peppermint, respectively for 18 years life span. However, the corresponding life cycle EPFs are 29.23, 33.13 and 38.98. This is a result of the various amounts of thermal energy output obtained for different batch sizes. EPF also depends on embodied energy that was consumed during fabrication for various life spans. A system with a lower EPF might be able to produce more energy than a system with a higher EPF. But for any system, if a design change increases the EPF, the yield also increases. A higher EPF value is recommended for the system's cost-effectiveness because it is obtained with an increase in life span. LCCE were obtained as 12.59%, 14.79% and 17.86% for 1500, 1700 and 1900 kg batch sizes of peppermint, respectively as depicted in Fig.4.22. Higher LCCE value was obtained for 1900 kg batch size as energy input was low with no sensible heat required.

Table 4.12 Energy measures CSD system for different batch sizes

Batch Sizes (kg)	Thermal efficiency (%)	EPF	Life cycle Conversion efficiency (%)
1500	0.67	29.23	12.59
1700	0.94	33.13	14.79
1900	1.06	38.98	17.863

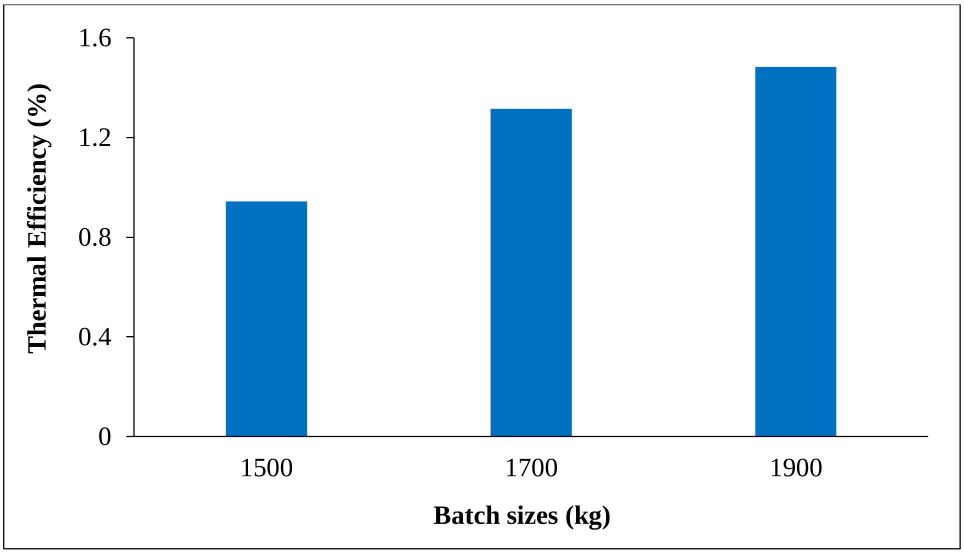


Fig.4.21 Thermal efficiency of CSD system for different batch sizes

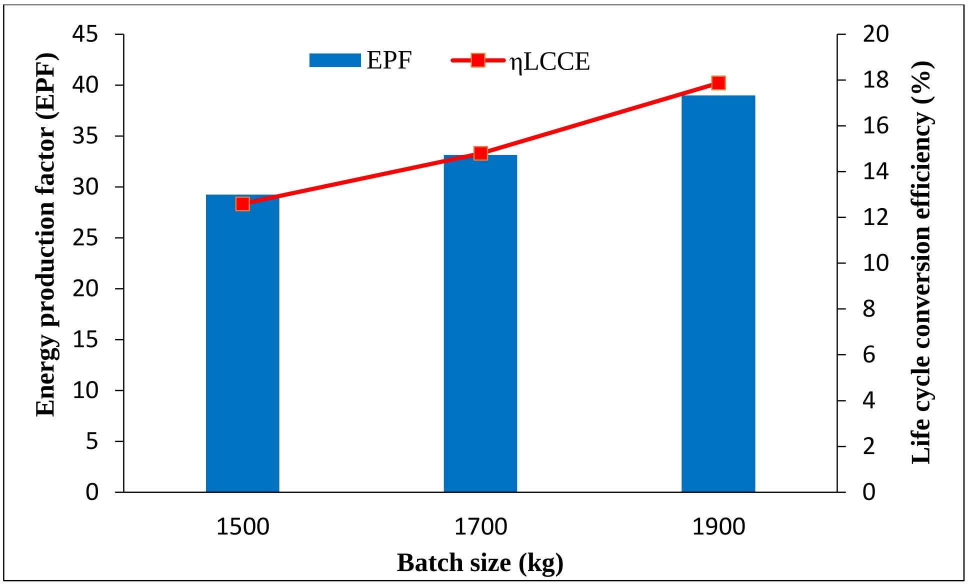


Fig.4.22 Energy production factor and LCCE variation with batch size

c. Net carbon credit

Annual CO_2 emissions and mitigation are estimated to 14591.93 and 23700, 28760 and 31600 kg for 1500, 1700 and 1900 kg, respectively, as shown in Fig.4.23. Estimated lifetime CO_2 emissions are 262.65 tonnes and mitigation is 426.6, 438.48 and 568.8 tonnes for 1500, 1700 and 1900 kg batch size, respectively as illustrated in Table 4.13. CO_2 emissions depend on the size of distillation unit (embodied energy), not the batch size; therefore, lifetime CO_2 emissions are constant for every batch size. As a result, it is determined that the system's net CO_2 mitigation during 18-year life duration is 163.94, 220.82 and 306.14 tonnes for 1500, 1700, and 1900 kg, respectively. Net CO_2 mitigation is higher for 1900 kg batch size as thermal energy output is higher (Fig.4.24). Net carbon credit earned is estimated to be ₹1,95,239 (US$2,383.93), ₹2,63,049 (US$3,211.91) and ₹3,61,518 (US$4,414.25) for 1500, 1700, and 1900 kg, respectively, if traded at the rate of 14.85US$/Tonne [88] as shown in Table 4.13. Net carbon credit earned for 1900 kg batch size is more than other batch sizes as CO_2 mitigation is more. The ability of CSD system to reduce CO_2 emissions is influenced by its size and extraction time. Less extraction time means more distillate output each day, which improves the system's annual energy production and, ultimately, CO_2 mitigation. However, as size of distillation system increases, the amount of embodied energy increases, which increases net CO_2 emissions from system. This means smaller system has a higher net CO_2 mitigation.

Table 4.12 Environmental parameters of CSD system for various batch sizes

Parameters	Batch Sizes (kg)		
	1500	**1700**	**1900**
EPBT (Years)	0.67	0.54	0.46
Embodied energy (kWh)	166237	166237	166237
Annual Thermal energy output (kWh)	270000	306000	360000
Annual CO_2 emissions (kg/year)	14592	14592	14592
Annual CO_2 mitigation (kg/year)	23700	26860	31600
Net CO_2 emissions over lifetime (Tonnes)	262.65	262.65	262.65
Net CO_2 mitigation over lifetime (Tonnes)	426.6	483.48	568.8
Net carbon credit earned (₹)	195293	263049	361518

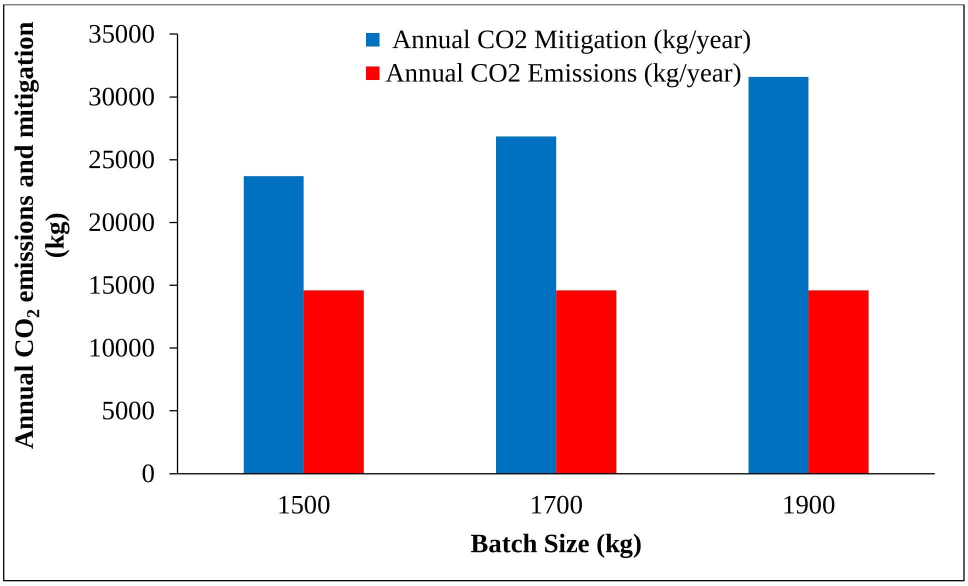


Fig.4.23 Annual CO_2 emissions and mitigation for CSD system for different batches

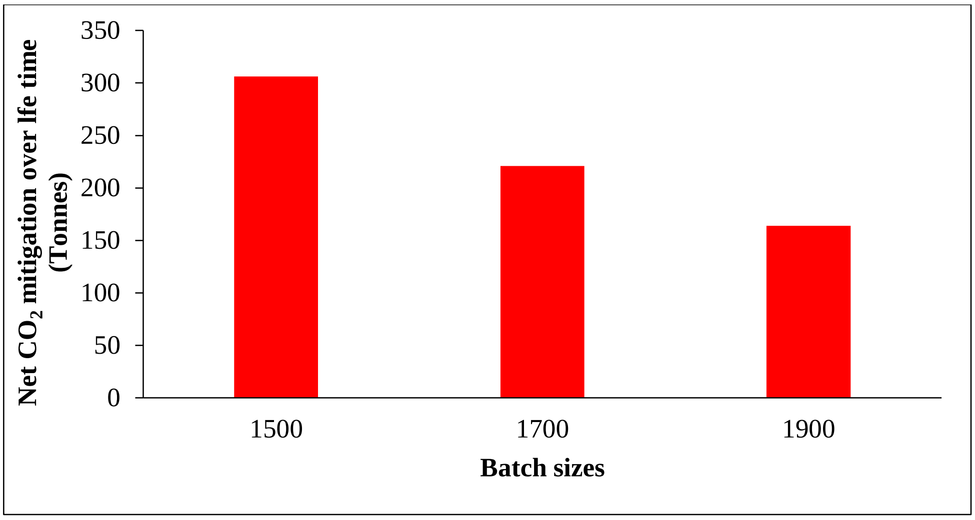


Fig.4.24 Net CO_2 mitigation over life time for CSD System for different batch sizes

4.2 SOLAR STEAM DISTILLATION SYSTEM

Energy distribution and power loss due to convection and radiation at different parts of a solar distillation unit to establish thermal energy balances of the solar system analysed during the distillation peppermint and eucalyptus plants. The results of performance evaluation for solar steam distillation system for essential oil extraction from peppermint and eucalyptus leaves based on energy, exergy, economic, exergoeconomic, environmental and enviroeconomic analysis have been presented and discussed in this section.

4.2.1 Variation in solar radiation and temperature

Experiments were performed from 10 hrs to 14 hrs on three different days for different batch sizes (2, 4, and 6 kg) and 15 kg of water. Solar radiation, focal point temperature, and amount of distillate were recorded during experiments. Fig.4.25 depicts the changes in solar radiation and focus point temperature with respect to the time for different days. Focus point temperature was maximum on day-1 at 13:45 hrs as solar radiation was maximum compared to day-2 and day-3. Due to clouds, the irradiation has altered slightly. The focal point temperature changes with respect to irradiance since both are directly proportional to each other. The highest beam radiation and focus point temperature were achieved as 1000.5 W/m^2 and 420°C, 950.5 W/m^2 and 384°C, 970.5 W/m^2 and 390.5°C on day-1, day-2 and day-3, respectively.

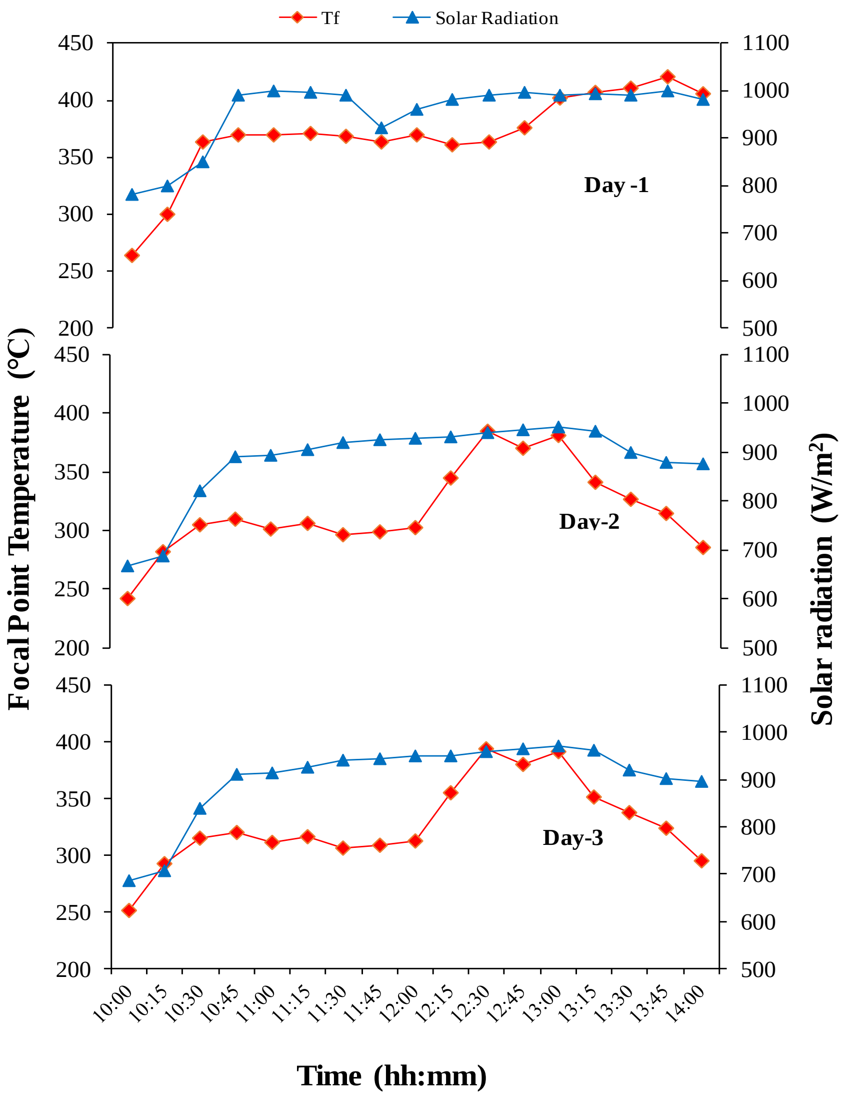
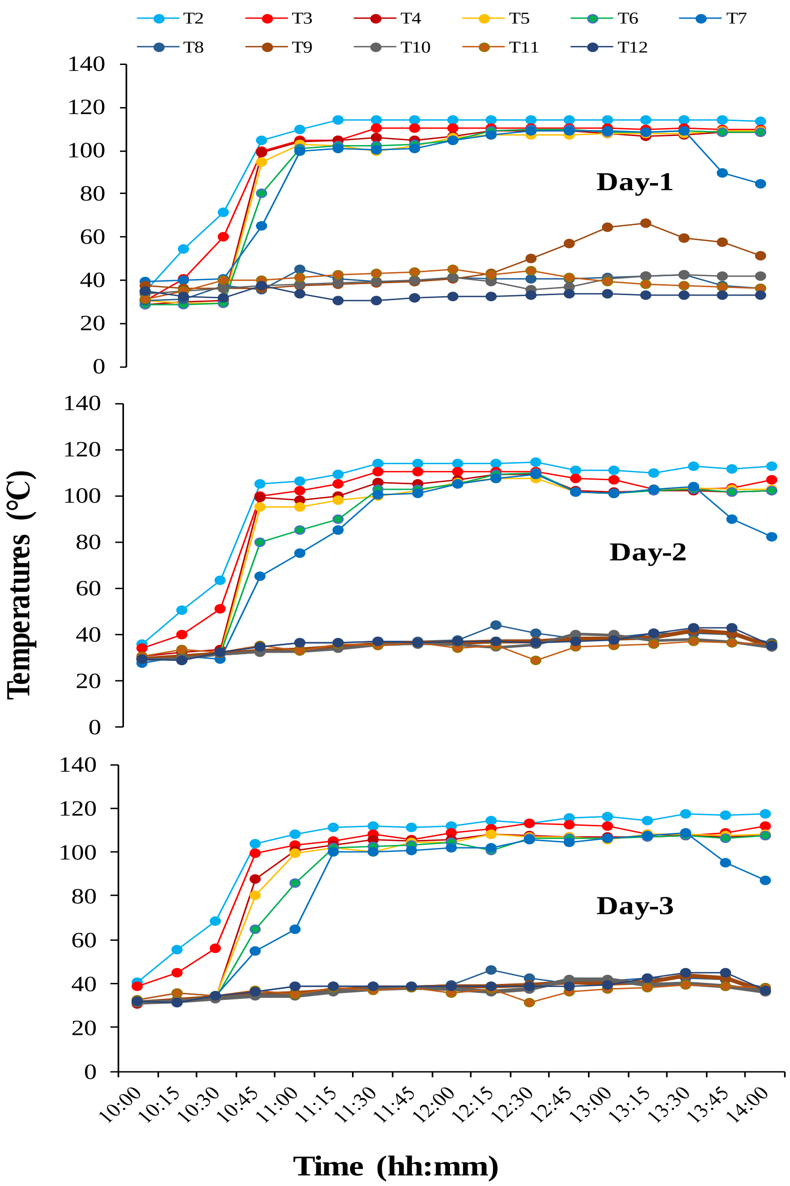


Fig.4.25 Variation in beam radiation and focal point temperature with time



T2 Temperature of water at middle of boiler
T3 Temperature of steam at outlet of boiler
T4 Temperature of steam at inlet to distillery
T5 Temperature of steam in middle of distillery
T6 Temperature of steam at outlet of distillery
T7 Temperature of oil and water vapors mixture at inlet to condenser
T8 Temperature of condensate at outlet of condenser
T9 Temperature of hot water outlet from condenser
T10 Temperature of cool water inlet to condenser
T11 Temperature of distillate collected
T12 Atmospheric temperature

Fig.4.26 Variation of different temperature with respect to time

Temperature variation at various point in boiler, distillery and condenser with respect to time is shown in Fig.26. Time required to obtain first drop of condensation is minimum for day-1 as temperature of vapour and oil mixture inlet to condenser (T7) reached 100°C at 11:15 hrs which is lesser as compared to day-2 and day-3.

Variation in distillate quantity with respect to time duration is shown in Fig.27. The volume distillate was 325 mL at start of distillation due to preheating of water and then increased intensely to around 500 mL at end of distillation considering 6 kg of peppermint (day-3). Three experimental procedures were carried out in order to compare the effects of an increasing batch size of peppermint. An increase in mass of peppermint plants increases the time required for oil to evaporate as packing density of leaves increases. Therefore, first drop of condensation was obtained earlier for day-1 (2 kg) as compared to day-2 (4 kg) and day-3 (6 kg). The volume of distillate is increasing with increase in batch size as shown in Fig.27.

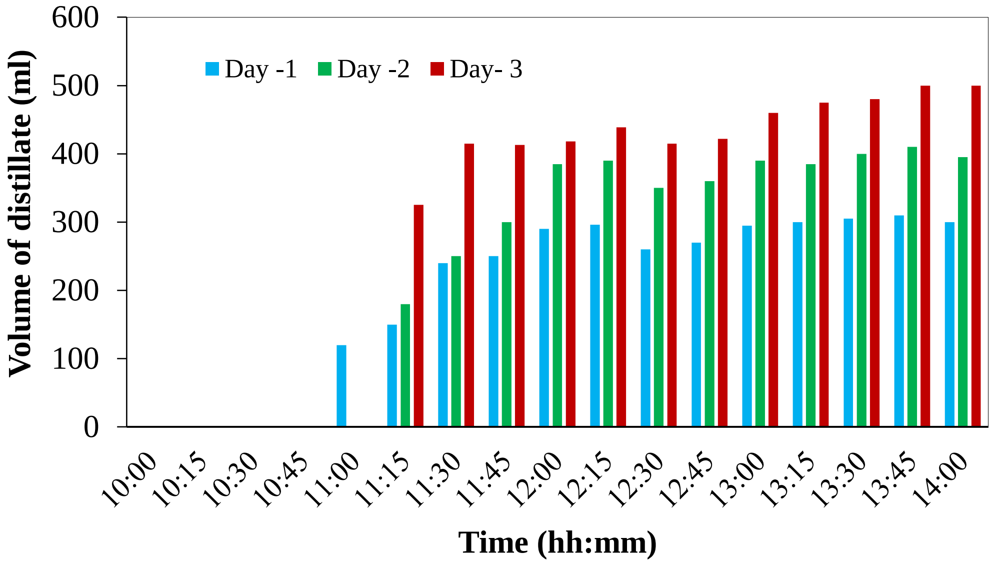


Fig.4.27 Yield obtained at intervals of 15 min

4.2.2 Energy analysis

Energy distribution at different parts of solar distillation system is shown in Fig.28. The Scheffler reflector was capable of collecting 26.31, 22.45, and 22.35 kWh of energy with average solar radiation of 100.5 W/m^2, 950.85 W/m^2, and 970.5 W/m^2 on day-1, day-2, and day-3, respectively for peppermint, while the corresponding values for eucalyptus were 18.05, 16.78, and 17.15 kWh with average radiation of 953.74, 882.52, and 902.61 W/m^2, respectively. Energy reflected from reflector to the bottom of boiler was calculated as 22.36 kWh, 19.08 kWh, and 18.99 kWh for peppermint. It indicates that 3.95 kWh, 3.37 kWh, and 3.36 kWh of energy were lost at the reflector due to reflection losses on day-1, day-2, day-3, respectively. While, for eucalyptus, 15.34 kWh, 14.26 kWh, 14.57 kWh of energy was reflected and 2.71 kWh, 2.52 kWh, 2.58 kWh of energy was lost on day-1, day-2, day-3, respectively. These losses have occurred because mirrors of 0.85 reflectivity were used in reflector. The energy on bottom of boiler was obtained as 15.36 kWh, 13.37 kWh, 13.65 kWh and 13.04 kWh, 12.12 kWh, 12.39 kWh for peppermint and eucalyptus on day-1, day-2, day-3, respectively. It means 7 kWh, 5.71 kWh, 5.34 kWh and 2.3 kWh, 2.14 kWh, 2.18 kWh of energy were lost due to scattering of rays from focus point on the way to boiler for peppermint and eucalyptus day-1, day-2, day-3, respectively. Moreover, 1.01 kWh, 1.02 kWh, 1.34 kWh and 1.31 kWh, 1.21 kWh, 1.24 kWh of energy were lost due to stainless steel reflectivity, remaining 14.35 kWh, 12.35 kWh, 12.31 kWh and 11.73 kWh, 10.91 kWh, 11.15 kWh of power conducted from bottom of boiler to inside surface of boiler for peppermint and eucalyptus, respectively on respective days. Energy eventually available for distillation of peppermint and eucalyptus on day-1, day-2, day-3, are estimated to be 13.95 kWh, 11.8 kWh, 11.81 kWh and 10.85 kWh, 9.72 kWh, 9.82 kWh, respectively indicating that some energy was lost due to conduction and convection. Results showed that energy available for distillation was maximum for peppermint on day-1 however, minimum was for eucalyptus on day-2.

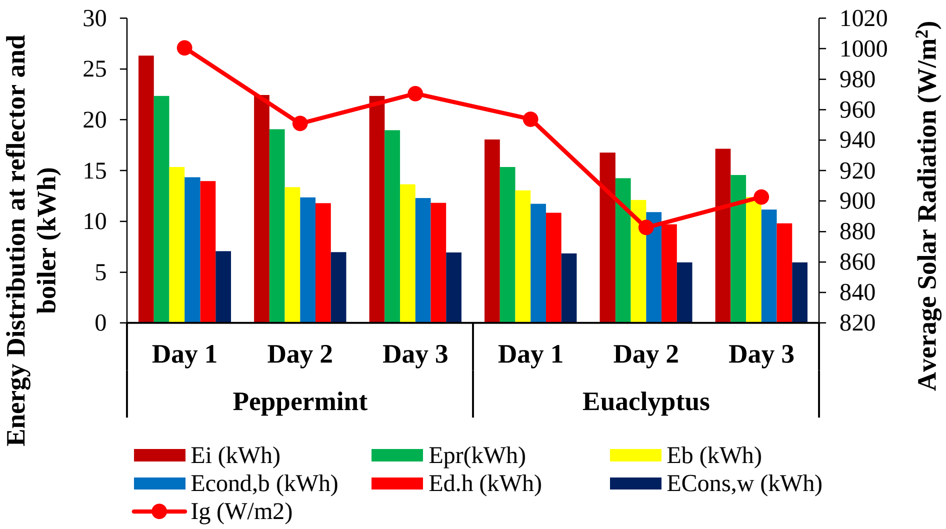


Fig.4.28 Energy distribution at different parts of system

Fig.29 and Fig.30 show the effect of batch sizes on energy distribution at steam line, condenser and different efficiencies of system for peppermint and eucalyptus leaves. It was clear from Fig.9 that energy lost ($E_{l,sl}$), energy outlet from steam line ($E_{o,sl}$), cooling energy required $E(_{l,c})$ and energy at outlet of condenser ($E_{o,c}$) was more for peppermint compared to eucalyptus leaves. Maximum efficiency of distillery was obtained as 97.21% for 2 kg of peppermint as energy at outlet of distillery was more whereas minimum efficiency was obtained as 88.07% for 6 kg eucalyptus leaves as outlet energy of still was minimum (Fig.8).

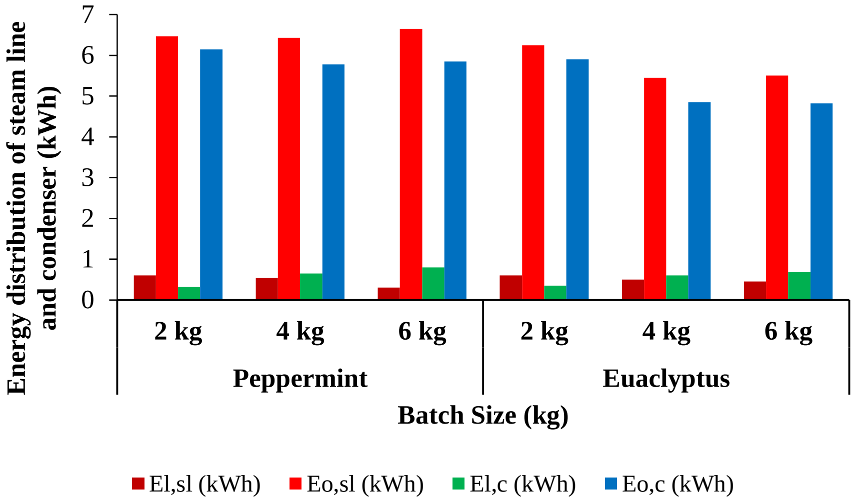


Fig.4.29 Energy distribution at steam line and condenser for different batch sizes

Maximum energy at outlet of steam line and minimum steam line losses were obtained as 6.65 and 0.3 kWh for 6 kg of peppermint. Therefore, efficiency of steam line was maximum for 6 kg batch of peppermint whereas minimum was calculated for 2 kg eucalyptus leaves due to maximum steam line losses. Cooling energy required was higher for higher batch size as temperature difference was more for higher batch size while energy at outlet of condenser was lower for higher batch size. Therefore, maximum efficiency of condenser was calculated as 95.05 % for 2 kg of peppermint whereas minimum was obtained as 87.63 % for 6 kg of eucalyptus leaves. Maximum and minimum system efficiency were calculated as 48.68% and 43.25 % for 2 kg of peppermint and 6 kg of eucalyptus, respectively.

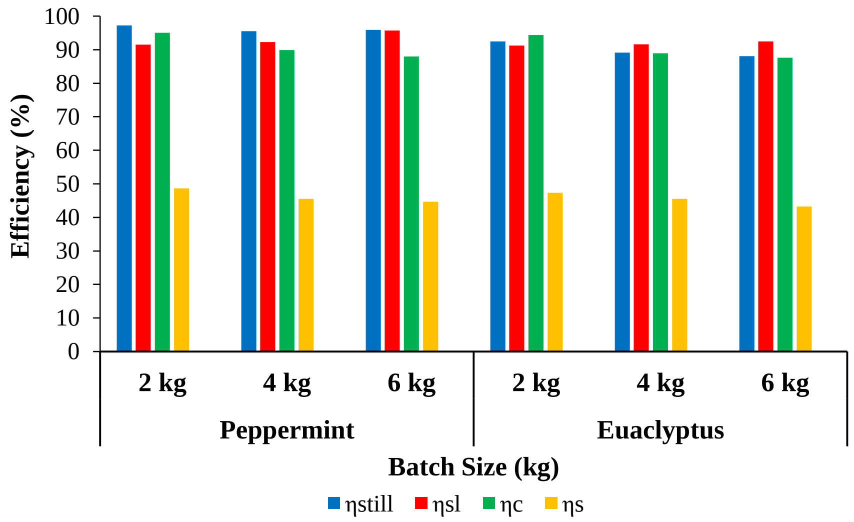


Fig.4.30 Efficiency of system and different parts of system

Table 4.13 Comparison of various parameters for 6 kg peppermint of present study with previous studies

Parameters	**Present study**	**Ezzarrouqy et al.** [13]	**Munir and Hensel** [14]
Energy available at solar collector (kWh)	22.35	20.23	18.6
Useful Energy, $E_{d.h}$ (kWh)	11.81	9.78	_
Energy required to condense the steam, $E_{o,c}$ (kWh)	5.85	5.36	_
Energy saving	2.67%	2.43%	_
Still efficiency, η_{still}	95.93%	94.83	_
Steam line efficiency, η_{sl}	95.68%	94.28%	_
Condenser efficiency, η_c	87.96%	87.76%	_
System efficiency, η_s (steam line is insulated)	44.65%	40.00%	33.21%

4.2.3 Exergy analysis

Energy and exergy analysis is an innovative method of evaluating and comparing systems. Exergy analysis is more effective than energy analysis in predicting the system efficiency. An exergetic analysis determines useful energy of system. For this objective, 6 kg of peppermint has been treated with steam of 15 kg water.

The difference between system's input energy and input exergy is very low during the 4 h of the experiment as shown in Fig.4.31. Results concluded that energy lost at Scheffler reflector is lower.

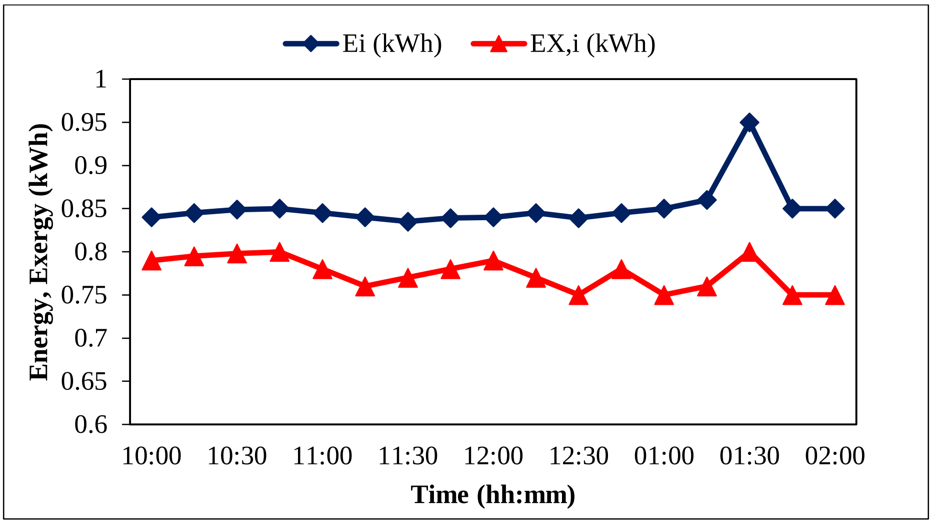


Fig.4.31 Input energy and input exergy variation of reflector with time

At the beginning of measurements, there was a substantial gap between energy output (0.15 kWh) and exergy output (0.05 kWh), as shown in Fig.4.32. This demonstrates that major losses occur at the beginning due to lack of insulation and preheating of bottom of boiler. These losses are reduced, and two curves become stable at 11h 30min. The losses are caused by the temperature difference between water and still over the time intervals studied.

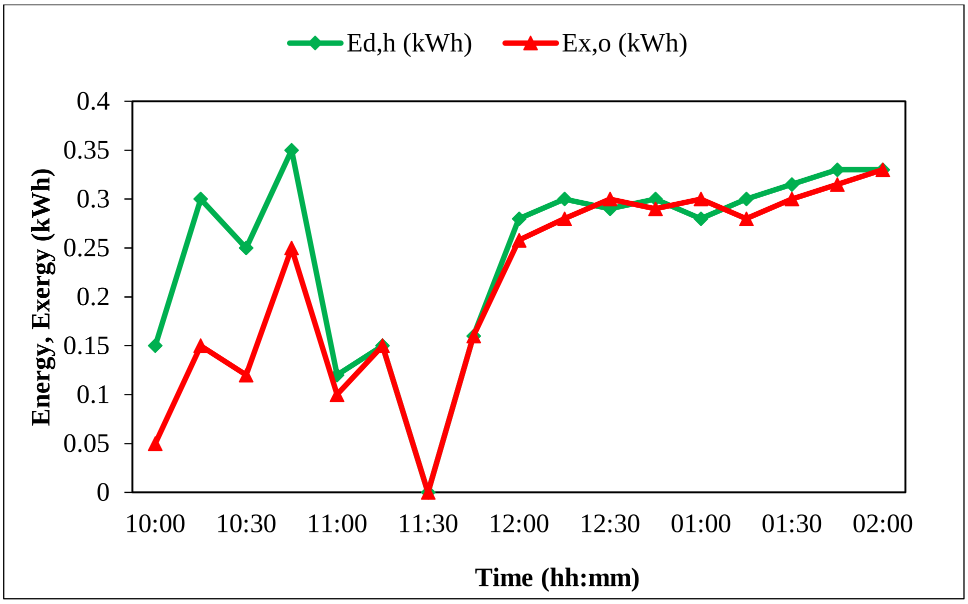


Fig.4.32 Output energy and output exergy variation of solar still with time

Various exergetic parameters such as exergy of sun (input exergy), exergy output, exergy loss and exergy efficiency have been calculated for different batch size of peppermint and eucalyptus leaves as shown in Fig.33. Highest input and output exergy was calculated as 14.68 kWh and 3.63 kWh for 2 kg and 6 kg peppermint, respectively. Exergy efficiency of system was obtained as 26.97%, 22.83%, 27.57% and 26.16%, 22.50%, 27.96 % for 2 kg, 4 kg, 6 kg of peppermint and eucalyptus, respectively.

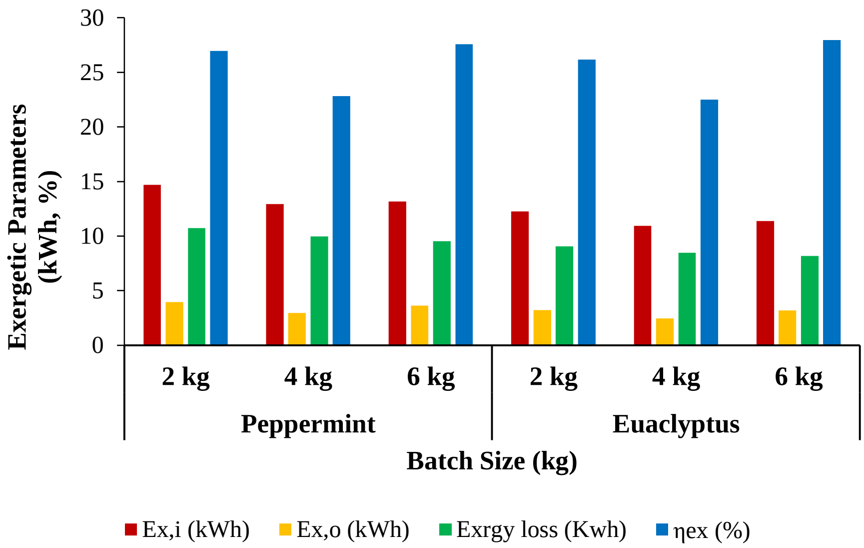


Fig.4.33 Effect of batch size of peppermint and eucalyptus on various exergetic parameters

Highest exergy efficiency was obtained as 27.96% for 6 kg of eucalyptus leaves as losses were minimum however lowest was 22.50% for 4 kg eucalyptus leaves as exergy output was minimum and losses were more.

4.2.4 Economic analysis

Results for various economic parameters such as IRR, ROI, PBP and cost per liter (CPL) values of SSDS are presented and discussed in this section. Moreover, effect of life span of SSDS on the CPL values is discussed.

a. Various costs analysis

Economic analysis was performed by considering 6 kg of peppermint. Various assumptions made in economic study of solar steam distillation system for essential oil extraction from peppermint leaves, producing 240 mL of essential oil per day as shown in Table.4.15. Total direct cost of system includes the cost of major equipment (boiler, distillery, and condenser) cost of piping, instrumentation, building and other non-depreciable items and was estimated to US$1200.42. Total indirect cost (Cost of design and construction) of system was estimated at US$646.38. Hence, total initial cost needed by a potential investor to establish a solar steam distillation system extracting 72 liters of peppermint oil per year (300 working days) amounts to US$1846.8 as shown in Fig.4.34.

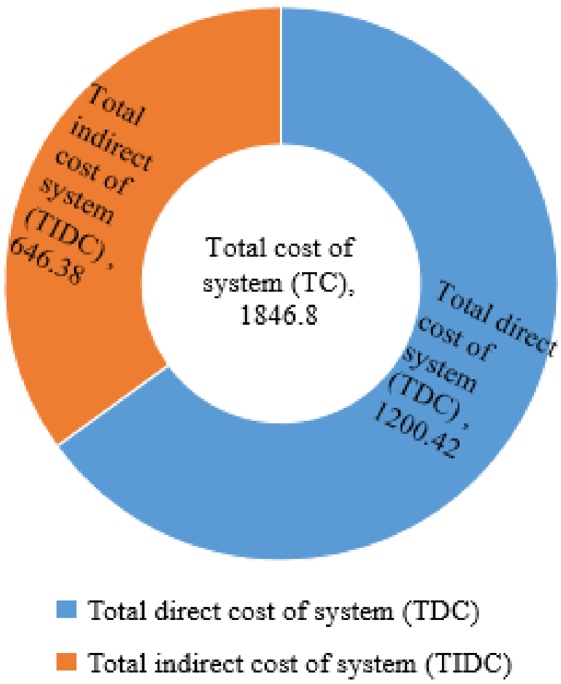


Fig.4.34 Total initial investment of system

As illustrated in Fig.4.37, the annual operating cost (AOC) of the system includes the cost of raw materials, the cost of fuel, the cost of utilities, and the cost of direct and indirect production. The anticipated maintenance cost (MC) and plant overhead cost (POC) were US$184.68 and US$187.68 per year, respectively, and represent 10% of the total initial expenditure. Local taxes (LT) and insurance (I) amounted to US$92.34 by considering 5% of the entire initial investment, respectively. As a result, the system's annual direct production cost (ADPC), which includes the MC, POC, LT, and I, amounts to US$554.04 as shown in Fig.4.35.

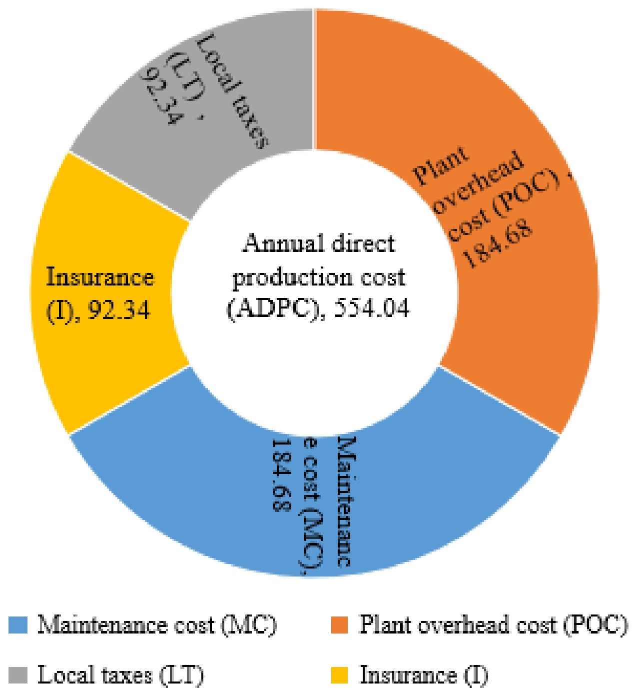


Fig.4.35 Annual direct production cost of system

R&D, general overhead, and sales expenses were each assessed at 4%, 4%, and 8% of the ADPC, and estimated to US$44.32, US$22.16, and US$22.16, respectively. As a result, the system's total annual indirect production cost (AIPC), which includes SE, GO, and R&D, was calculated to be US$118.06 as shown in Fig.4.36.

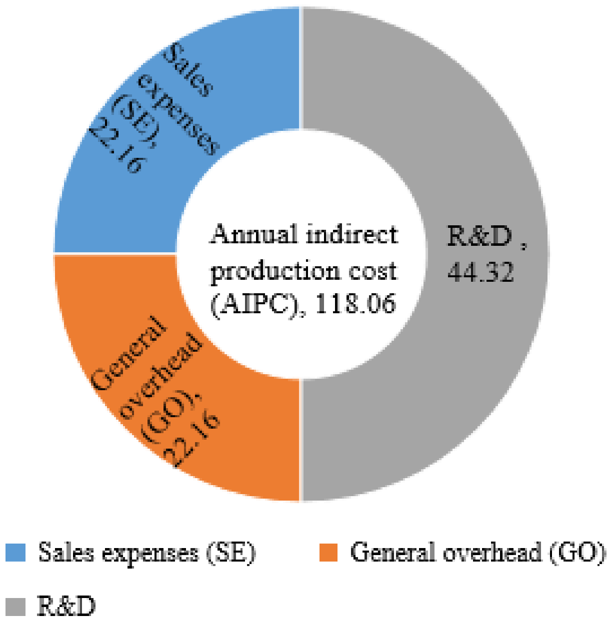


Fig.4.36 Annual indirect production cost of system

Raw material (RM) used in distillation system was peppermint leaves with requirement of 3600 kg/year, amounting to US$648 at US$0.18 per kg. Cost of utilities (UC) was considered as US$30.36. Hence, AOC of system, including RM, UC, ADPC and AIPC to extract 72 liters of peppermint oil was estimated at US$492,608.17, as depicted in Fig.4.37.

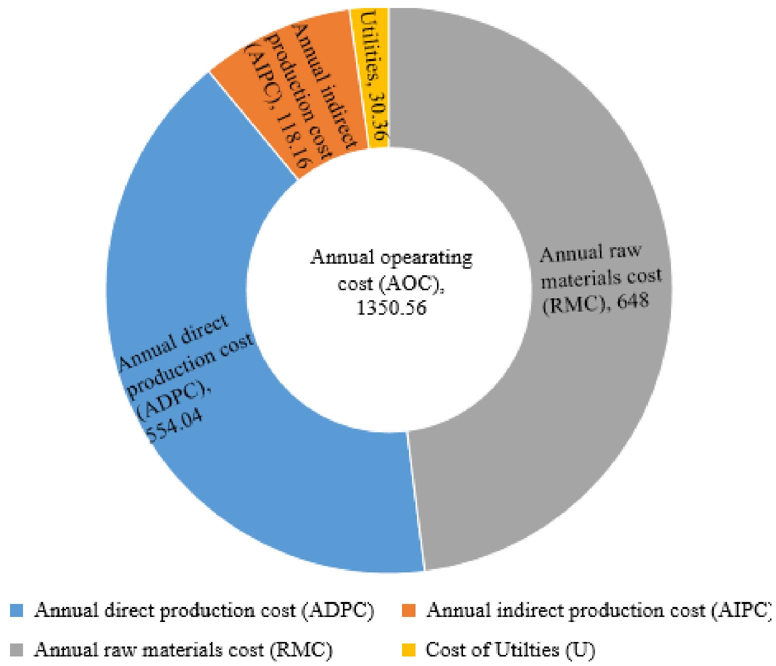


Fig.4.37 Annual operating cost of system (US$)

Annual production of essential oil from system was 72 liters based on daily production of 240 milliliters in two batches for 4h of operation per batch. The estimated selling price of essential oil was US$1733.04 per year at US$24.07 per liter. Annual estimated operational profit gained from system was US$382.48, as depicted in Table 4.16. Profit before tax (PBT) was estimated at US$6927.81 by considering annual depreciation of US$384.02 and life span of 18 years. Profit after tax (PAT) was gained as US$5680.81 at a tax rate of 18%. PAT is estimated to increase in successive years of operation by enhancing utilization capacity of system or optimizing operational parameters, including labor utilization.

The estimated return on investment (ROI) was 14.03%, with a profit margin of 14.95% and return of equity at estimated value of equity of 20% of total investment was 369.7%. Internal rate of return was positive at 18.77% over the projected economic life span of 25 years. Annual cash flow and payback period (PBP) were US$325.6 and 5.67 years, respectively. Table 4.16 illustrates summary of profit analysis.

Table 4.14 Assumptions in economic study of pilot plant

Items	Assumed Value
Plant overhead cost (POC)	10% of Total Cost
Local taxes (LT)	5% of Total Cost
Insurance (I)	5% of Total Cost
Sales expenses (SE)	4% of Annual Direct Production Cost
General overhead (GO)	4% of Annual Direct Production Cost
R&D	8% of Annual Direct Production Cost
Utilities (U), US$	30.36
Tax	18%
Equity	@20
Life of system	25 Years

Table 4.15 Summary of various costs associated with profit analysis

Items	Value	Rate	Cost (US$)	Total Amount (US$)
Annual production of essential oil (liters)	72			
Annual selling price (ASP)		24.07(US$/L)		1733.04
Operational profit (OP)				**382.48**
Life of system (LS), Years	25			
Depreciation (D)			66.48	
Profit before tax (PBT)				316.00
Tax (T)		18%	56.88	
Profit after tax (PAT)				**259.12**
Return on investment (ROI), %				**14.03**
Profit margin (PM), %				14.95
Equity		@20%		
Return on equity (ROE), %				369.37
Annual cash flow (ACF)				325.6
Payback period (PBP), Years				**5.67**
Breakeven point (BEP)				4.82

Internal rate of return (IRR), %	**18.77**

b. Cost of essential oil per liter (CPL)

Cost estimation per liter for system producing 240 mL and 200 mL of essential oil per day from peppermint and eucalyptus leaves, respectively has been established in present study. Cost per liter (CPL) values for peppermint at 5, 10 and 15% interest rate are estimated to be 1.89, 3.05 and 4.34 US$/L while for eucalyptus, the values are 2.27, 3.66 and 5.20 US$/L, respectively as shown in Table 4.17. Results showed that CPL values for eucalyptus oil were more than that of peppermint oil because yield of peppermint oil was higher than that of eucalyptus oil. The estimated uniform annual cost (UAC) for higher interest rate was higher, therefore, CPL values were higher for higher interest rate. Finally, this research shows that the solar steam distillation system for essential oil extraction from peppermint leaves is economically attractive based on CPL values.

Table 4.16 Analysis of cost per liter for peppermint and eucalyptus oil

n (Years)	i (%)	TC (US$)	FAC (US$)	AMC (US$)	ASV (US$)	UAC (US$)	$Pn_{,P}$ (L)	$Pn_{,e}$ (L)	CPL_p (US$/L)	CPL_E (US$/L)
25	5	1846.8	131.03	13.10	7.73	136.39	72	60	1.89	2.27
25	10	1846.8	203.45	20.34	3.75	220.04	72	60	3.05	3.66
25	15	1846.8	285.69	28.56	1.73	312.53	72	60	4.34	5.20

The effect of life span of system on cost per liter for peppermint and eucalyptus essential oil is shown in Table 6. SSDS for peppermint and eucalyptus oil extraction is economically assessed at different interest rates (5, 10, and 15%) and lifespan (20, 25 and 30 years) as shown in Table 4.18. The results revealed that for the system lifespan of 20, 25, and 30 years, the uniform annual costs (UAC) were obtained as US$151.84, US$136.39, and US$126.59, respectively at same rate of interest of 5%. Moreover, it was found that the cost per litre (CPL) decreases as the system's lifespan increases. Cost per litre values of produced peppermint oil were 2.10, 1.89 and 1.75 US$/L for 20, 25, and 30 years of lifespan, respectively, at the same interest rate (5%) while for eucalyptus oil, the corresponding values were 2.53, 2.27 and 2.10 US$/L, respectively. It was observed from results that CPL values for peppermint oil were reduced by 10 and 16.66% with increase in lifespan by 5 and 10 years, respectively, whereas for eucalyptus oil, the corresponding values were decreased by 10.27 and 16.99 % with increase in corresponding lifespan of system, respectively.

Table 4.17 Effect of life span of system on cost per litre of essential oil

n (Years)	i (%)	TC (US$)	FAC (US$)	AMC (US$)	ASV (US$)	UAC (US$)	$Pn_{,P}$ (L)	$Pn_{,e}$ (L)	CPL_p (US$/L)	CPL_E (US$/L)
					20 Years					
20	5	1846.8	148.19	14.81	11.17	151.84	72	60	2.10	2.53
20	10	1846.8	216.92	21.69	6.44	232.16	72	60	3.22	3.86
20	15	1846.8	295.04	29.50	3.605	320.94	72	60	4.45	5.34
					25 Years					
25	5	1846.8	131.03	13.10	7.73	136.39	72	60	1.89	2.27
25	10	1846.8	203.45	20.34	3.75	220.04	72	60	3.05	3.66
25	15	1846.8	285.69	28.56	1.73	312.53	72	60	4.34	5.20
					30 Years					
30	5	1846.8	120.13	12.01	5.559	126.59	72	60	1.75	2.10
30	10	1846.8	195.90	19.59	2.24	213.25	72	60	2.96	3.55
30	15	1846.8	281.26	28.12	0.849	308.54	72	60	4.28	5.14

4.2.5 Exergoeconomic analysis

The outcomes of exergoeconomic evaluation of solar steam distillation system (SSDS) producing 240 mL of peppermint oil and 200 mL of eucalyptus essential oil per day are shown in Table 4.19. The exergoeconomic parameter for peppermint at interest rate of 5, 10, and 15% were estimated to be 7.99, 4.95 and 3.48 kWh/US$, respectively, while for eucalyptus the exergoeconomic parameter for corresponding interest rates was 6.99, 4.33 and 3.05 kWh/US$, respectively. The finding showed that exergoeconomic parameter was higher for peppermint than that of eucalyptus as exergy output was higher for peppermint than that of eucalyptus. Exergoeconomic parameters were estimated at different interest rate and observed that it was lower for higher interest rate as uniform annual cost was higher for higher interest rate. Moreover, it was concluded from results that exergoeconomic parameter for peppermint oil was 14.3 % more than that of eucalyptus oil for 5% of interest rate.

Table 4.18 Exergoeconomic parameter estimation of SSDS for peppermint and eucalyptus oil

i (%)	n (Years)	UAC (US$)	$E_{xo,p}$ (kWh)	$E_{xo,e}$ (kWh)	$R_{ex,p}$ (kWh/US$)	$R_{ex,e}$ (kWh/US$)
5	25	136.39	1089.9	954	7.99	6.99
10	25	220.04	1089.9	954	4.95	4.33
15	25	312.53	1089.9	954	3.48	3.05

The effect of lifespan on exergoeconomic parameter of SSDS for peppermint and eucalyptus essential oil extraction at different rate of 5, 10, and 15% is illustrated in Table 4.20. Exergoeconomic parameter for peppermint oil at same rate of interest (5%) was obtained as 7.17, 7.99 and 8.60 kWh/US$ for life span of 20, 25 and 30 years, respectively whereas for eucalyptus oil, the values of exergoeconomic parameter at same interest rate were 6.28, 6.99 and 7.53 kWh/US$ for corresponding lifespan of system, respectively. It was observed from Table 4.20 that exergoeconomic parameter was more for higher lifespan of system for the specific rate of interest (i.e. 5%). It happens as uniform annual cost (UAC) at same interest rate is decreasing with increase in lifespan with constant exergy output. Finally, it was concluded that exergoeconomic parameter at the same interest rate of 5% for peppermint oil was increased by 11.43 and 19.94% with increase in lifespan of system by 5 and 10 years, respectively. Whereas, the value of exergeconomic parameter for eucalyptus oil at same interest rate of 5% was increased by 11.30 and 19.90% with increase in lifespan of system by 5 and 10 years, respectively.

Table 4.19 Effect of lifespan of system on exergoeconomic parameter for peppermint and eucalyptus oil

i (%)	n (Years)	UAC (US$)	$E_{xo,p}$ (kWh)	$E_{xo,e}$ (kWh)	$R_{ex,p}$ (kWh/US$)	$R_{ex,e}$ (kWh/US$)
			20 Years			
5	20	151.84	1089.9	954	7.17	6.28
10	20	232.16	1089.9	954	4.69	4.10
15	20	320.94	1089.9	954	3.39	2.97
			25 years			
5	25	136.39	1089.9	954	7.99	6.99
10	25	220.04	1089.9	954	4.95	4.33
15	25	312.53	1089.9	954	3.48	3.05
			30 Years			
5	30	126.59	1089.9	954	8.60	7.53
10	30	213.25	1089.9	954	5.11	4.47
15	30	308.54	1089.9	954	3.53	3.09

4.2.6 Environmental analysis

Results for various environmental parameters such as EPBT, energy matrices, CO_2 emissions, CO_2 mitigations and total carbon credit earned have been presented and discussed in this section.

a. Energy payback time (EPBT)

Fig.4.38 illustrates the effect of batch size of peppermint and eucalyptus leaves on annual energy output and energy payback time (EPBT). It was observed from Fig.16 that energy output for peppermint and eucalyptus was increased with an increase in batch size while energy payback time was decreased. Highest energy output was obtained as 180 and 150 kWh for 6 kg batch size of peppermint and eucalyptus, respectively whereas minimum value of energy payback time was estimated to be 8.11 and 10.14 years for 6 kg peppermint and eucalyptus leaves, respectively. It means energy payback time was just 2 years more for eucalyptus than peppermint. It indicated that energy payback time was lower for higher batch sizes as energy output was more for higher batch sizes for constant embodied energy. Energy output was more for peppermint compared to eucalyptus due to the value of essential oil yield obtained being more for peppermint than eucalyptus leaves.

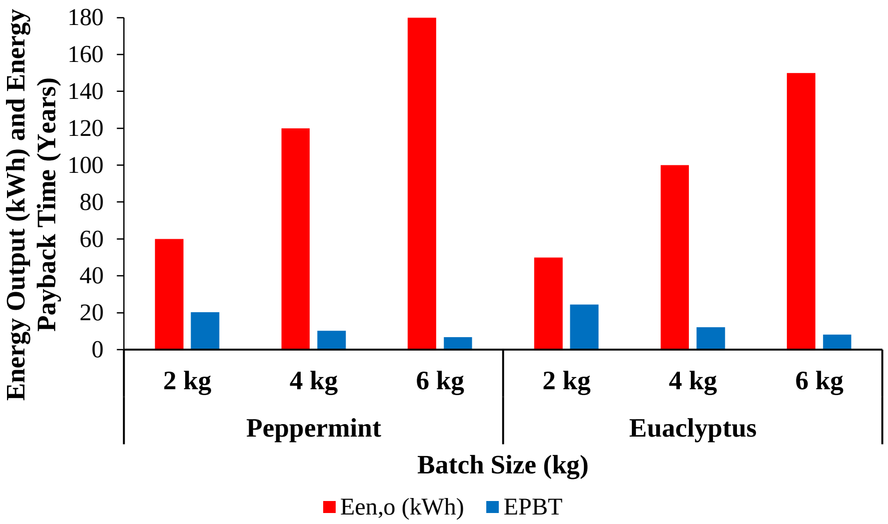


Fig.4.38 Effect of batch size of peppermint and eucalyptus on energy output and energy payback time

b. Energy Matrices

The effect of batch size of peppermint and eucalyptus on energy matrices of SSDS such as thermal efficiency, energy production factor (EPF) and life cycle conversion efficiency (LCCE) is shown in Fig.4.39. It was found from Fig.4.39 that the value of thermal efficiency, EPF and LCCE were more for higher batch sizes due to higher energy output for both medicinal plants. The highest values of thermal efficiency, EPF and LCCE were calculated as 27.51%, 3.69 and 6.70%, respectively, for 6 kg of peppermint while the corresponding values for eucalyptus were obtained as 24.43%, 3.07 and 5.51%, respectively. It indicates that thermal efficiency, EPF and LCCE of SSDS were reduced by 11.17, 16.8 and 17.76%, respectively for eucalyptus oil extraction than peppermint oil for constant batch size (i.e. 6 kg) as yield of peppermint oil was higher compared to eucalyptus oil. Moreover, thermal efficiency, EPF and LCCE were increased by 48.62, 50 and 82.56%, respectively when batch size of peppermint was increased from 4 kg to 6 kg.

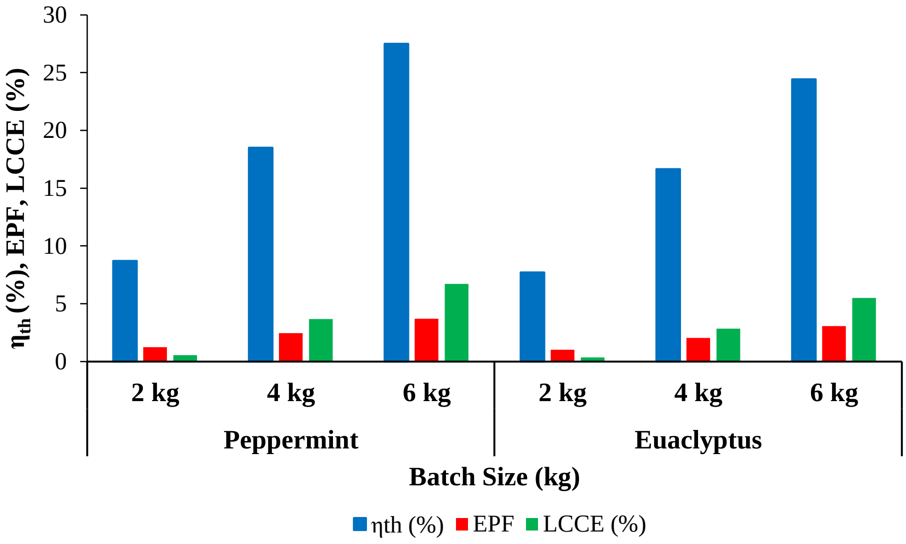


Fig.4.39 Variation in energy matrices of SSDS for peppermint and eucalyptus with batch size

c. Carbon Trading and environmental parameters

Environmental benefits of SSDS for peppermint and eucalyptus oil in terms of carbon emissions are assessed in present study. Environmental parameters such as CO_2 emissions, CO_2 mitigation and net carbon credit earned (tons) for various batch size of peppermint and eucalyptus are calculated for lifespan of SSDS and discussed in this section as shown in Fig.4.40. Moreover, Table 4.21 illustrates that energoenvironmental and exergoenvironmental parameters for various batch sizes of SSDS for peppermint and eucalyptus essential oil are evaluated based on energy and exergy approach, respectively. Results revealed that CO_2 mitigated over the lifespan from SSDS for peppermint oil and eucalyptus oil based on energy approach was calculated as 2.37, 4.74, 7.11 tons of CO_2 and 1.97, 3.95, 5.9 tons of CO_2 for 2, 4 and 6 kg batch size, respectively. Whereas, the corresponding values based on exergy approach for peppermint and eucalyptus oil were 0.15, 0.11, 0.14 tons CO_2/year and 0.12, 0.09, 0.12 tons CO_2/year, respectively. It can be observed from Fig.4.40 that maximum total carbon credit earned for SSDS was obtained as ₹6354.86 (US$77.01) and ₹4902.74 (US$59.41) for 6 kg of peppermint and eucalyptus, respectively as net CO_2 mitigation from system was more for peppermint than eucalyptus. Since energy and exergy output over lifespan from system was more for peppermint oil extraction compared to eucalyptus oil, hence system mitigates more CO_2 for peppermint oil extraction compared to eucalyptus oil based on energy and exergy approach. It can be concluded that system is environmentally feasible for peppermint oil extraction with higher batch size.

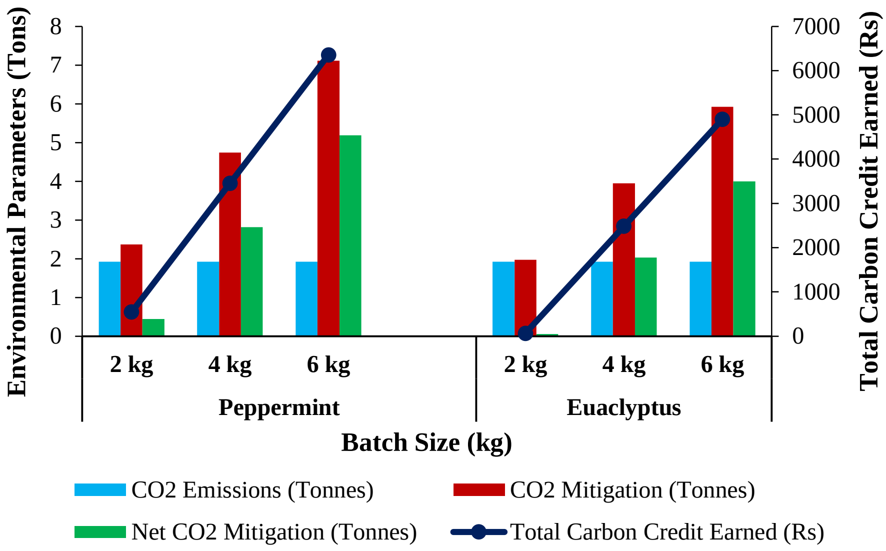


Fig.4.40 Effect of batch size of eucalyptus and peppermint on environmental parameters

Table 4.20 Energoenvironmental and exergoenvironmental evaluations based on energy and exergy approach

Medicinal Plants	**Peppermint**			**Eucalyptus**		
Batch Size	**2 kg**	**4 kg**	**6 kg**	**2 kg**	**4 kg**	**6 kg**
Energoenevironmental (tons of CO_2)	2.37	4.74	7.11	1.975	3.95	5.925
Exergoenvironmental (tons of CO_2)	0.15	0.11	0.14	0.12	0.09	0.12

4.2.7 Enviroeconomic analysis

Enviroeconomic parameters of SSDS system for various batch sizes of peppermint and eucalyptus oil extraction based on energy and exergy approach are shown in Table 4.22. Enviroeconomic parameter based on energy approach was estimated to be US$34.36, US$68.73, US$103.09 and US$28.63, US$57.27, US$85.91 for 2, 4, 6 kg of peppermint and eucalyptus, respectively. whereas, corresponding values based on exergy approach were estimated to be US$2.32, US$1.73, US$2.13 and US$1.88, US$1.44, US$1.8 for 2, 4, 6 kg of peppermint and eucalyptus, respectively.

Table 4.21 Enviroeconomic parameters based on energy and exergy approach

Medicinal Plants	Peppermint			Eucalyptus		
Batch Size	**2 kg**	**4 kg**	**6 kg**	**2 kg**	**4 kg**	**6 kg**
Energoenviroeconomic (US$)	34.36	68.73	103.09	28.63	57.27	85.91
Exergoenviroeconomic (US$)	2.3228	1.73	2.13	3.05	2.02	3.09

Chapter five represents the conclusion of the entire observations made for both the proposed systems in this Thesis. Further, the entire observations are concluded with recommendations for future work that may enlighten the researchers to move ahead for further possible developments in this field for the betterment of the environment, and society.

CHAPTER: 5

CONCLUSIONS AND FUTURE RECOMMENDATIONS

CHAPTER: 5

CONCLUSIONS AND FUTURE RECOMMENDATIONS

This chapter represents the conclusions of the entire research work made for both systems. The solar steam distillation system shows the best performance in overall perspectives than the conventional distillation system. Further, the entire observations are concluded with future recommendations that may enlighten the researchers to move ahead for the additional possible developments in this field for the betterment of society, environment, and the sustainable growth of human beings.

5.1 CONCLUSIONS

The conventional distillation system has been analyzed in terms of performance, energy, environmental and economic assessment under different batch size of peppermint using energy balance, mass balance and characteristics equations. Process parameters of conventional distillation system have been optimized using RSM. Based on the present study, following conclusions are framed:

I. System productivity (20L), maximum hourly thermal efficiency (2%), extraction efficiency (41.5%) and 0.461% (w/w) maximum essential oil yield were obtained for batch size of 1900 kg.

II. Thermal efficiency, cumulative system productivity, EOY and extraction efficiency are increased with the increase in plant batch size.

III. Average increase in total productivity, extraction efficiency, and EOY was 49.25%, 1% and 26%, with an increase in batch size from 1500 kg to 1900 kg.

IV. A quadratic polynomial model was developed for predicting the extraction yield and showed a good agreement between actual and predicted values of extraction yield (R^2=0.9960)

V. As per ANOVA, the impacts of extraction time, batch size and their interactions were the key process parameters shown to be statistically significant in influencing the essential oil yield.

VI. Maximum oil yield of 1.06% was obtained at optimal parameters at 300 min ET and 1807.5 kg batch size.

VII. Annual EPFs are estimated to be 1.62, 1.84 and 2.16 for 1500, 1700 and 1900 kg batch sizes of peppermint, respectively, for 18 years life span. However, the corresponding life cycle EPFs are 29.23, 33.13 and 38.98.

VIII. LCCE was obtained as 12.59%, 14.79% and 17.86% for 1500, 1700 and 1900 kg batch sizes of peppermint.

IX. Annual operational profit and profit after tax of pilot plant producing 80 liters of essential oil per day were estimated at US$7,311.8 and US$5,680.8.

X. Estimated return on investment (ROI) was 73.9 % with a profit margin of 1.13% and internal rate of return was calculated as 85.7% with 1.26 years payback period of pilot plant.

XI. Distillation system has a total embodied energy of 166237 kWh (595484 MJ). Mild steel, which accounts for around 98% of the total embodied energy, is used to construct the distillery, boiler, condenser and supporting structures.

XII. Estimated lifetime CO_2 emissions are 262.6 tonnes and mitigation are 426.6, 438.5 and 568.8 tonnes for 1500, 1700 and 1900 kg batch sizes, respectively. CO_2 mitigation depends on the batch size since thermal energy output is higher for higher batch size; therefore, lifetime CO_2 mitigation is higher for the 1900 kg batch size.

XIII. Net carbon credit earned is estimated to be ₹1,95,239 ($2,383.9), ₹2,63,049 ($3,211.9) and ₹3,61,518 ($4,414.3) for 1500, 1700, and 1900 kg, respectively, if traded at the rate of 14.85$/Tonne.

In present study, a solar energy integrated distillation system for essential oil extraction from peppermint and eucalyptus is evaluated based on energy, exergy, economic, exergoeconomic, environmental and enviroeconomic point of view. Moreover, effect of batch size of peppermint and eucalyptus on system efficiency, exergetic parameters and environmental parameters has been discussed. Following conclusions have been drawn on the basis of present study.

I. Maximum and minimum system efficiency was calculated as 48.68% and 43.25 % for 2 kg of peppermint and 6 kg of eucalyptus, respectively, whereas highest and lowest exergy efficiency of system was determined as 27.96 % and 22.50 % for 6 kg and 4 kg of eucalyptus leaves, respectively.

II. The estimated return on investment (ROI), Internal rate of return (IRR) and payback period (PBP) of SSDS producing 72 liters of peppermint oil per year were 14.03%, 18.77% and 5.67 years, respectively over the projected economic life span of 25 years.

III. Cost per litre (CPL) values of produced peppermint oil at the same interest rate (5%) were 2.10, 1.89 and 1.75 US$/L for 20, 25, and 30 years of lifespan, respectively while for eucalyptus oil, the corresponding values were 2.53, 2.27 and 2.10 US$/L, respectively.

IV. CPL values for peppermint oil were reduced by 10 and 16.66% with increase in lifespan by 5 and 10 years, respectively, whereas for eucalyptus oil, the corresponding values were decreased by 10.27 and 16.99 %, respectively.

V. Exergoeconomic parameter for peppermint oil was enhanced by 11.43 and 19.94% with increase in lifespan of system by 5 and 10 years, respectively at same interest rate of 5% while the corresponding values for eucalyptus oil were increased by 11.30 and 19.90%, respectively.

VI. Thermal efficiency, EPF and LCCE of SSDS were reduced by 11.17, 16.8 and 17.76%, respectively for eucalyptus oil extraction than peppermint oil for constant batch size (i.e. 6 kg)

VII. CO_2 mitigated over the lifespan from SSDS for peppermint oil and eucalyptus oil based on energy approach was calculated as 2.37, 4.74, 7.11 tons of CO_2 and 1.97, 3.95, 5.9 tons of CO_2 for 2, 4 and 6 kg batch size, respectively. Whereas, the corresponding values based on exergy approach were 0.15, 0.11, 0.14 tons CO_2/year and 0.12, 0.09, 0.12 tons CO_2/year, respectively.

It can be concluded from the results that SSDS system appears more effective for peppermint oil extraction than eucalyptus oil from economic and environmental point of view. Moreover, SSDS showed the best performance for peppermint oil extraction. This research will be helpful for researchers and investors to find out various energy-saving potentials at different parts of system and to establish a cost-effective, environment-friendly solar distillation system for essential oil extraction from aromatic and medicinal plants. Moreover, the developed system will help in creating job opportunities for youth in rural areas and increase farmer’s income.

5.2 RECOMMENDATIONS FOR FUTURE WORK

The energy storage-based solar steam distillation system can be developed as solar radiation is not available during night hours and cloudy days. Moreover, development of self-sustainable solar energy-integrated steam distillation system is recommended.

The solar distillation system has been analysed under different batch size of peppermint in present study. The proposed system can be analysed at different variable parameters such as capacity of boiler inlet water and different condenser water inlet flow rate to predict optimum water in boiler and inlet flow rate to condenser for best performance of the system. Highest temperature in distillery can be optimized in further study to find optimum maximum temperature in distillery to maintain the quality of essential oil.

Furthermore, experimental practices are always recommended along with the CFD analysis for the proposed model (solar steam distillation system) to design and check its validity, competency, and sustainability for the continuous existence in the competitive market for the production of essential oil and the corresponding responses under the variable meteorological conditions.

Moreover, Proximate analysis can be performed on essential oil extracted from conventional and solar steam distillation system to find out various constituents of essential oil by quality and quantity.

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PUBLICATIONS

International & National Journal/Conference Paper Published (04+ 04 = 08)

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1. **Ravi Kant** and Anil Kumar. Thermodynamic Analysis of Solar Assisted Steam System for Peppermint Oil Extraction. **Journal of Food Process Engineering**-Wiley https://doi.org/10.1111/jfpe.14228. **SCI Impact Factor 2.889 (SCIE)**
2. **Ravi Kant** and Anil Kumar. Review on Essential Oil Extraction from Aromatic and Medicinal Plants: Techniques, Performance and Economic Analysis. **Sustainable Chemistry and Pharmacy**-Elsevier Volume 30, December 2022, 100829. https://doi.org/10.1016/j.scp.2022.100829. **SCI Impact Factor 5.464 (SCIE)**
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1. **Ravi Kant** and Anil Kumar. Empirical Relation to Predict of Essential Oil Yield in Conventional Distillation System. Int. conference "Recent Advances in Materials, Manufacturing and Thermal Engineering", Delhi: RAMMTE-2022, July 8-9, 2022 **(SCOPUS)**
2. **Ravi Kant** and Anil Kumar. Energetic and Exergetic Analysis of Solar Steam Distillation System for Peppermint Oil Extraction. International Conference on Thermo-Fluids and System Design (ICTFSD 2022), 01 – 02 February 2022 organized by Department of

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Thermodynamic analysis of solar assisted steam distillation system for peppermint oil extraction

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Abstract

Scheffler reflector (10 m^2) integrated peppermint oil (PO) extraction distillation system is developed. Optical loss in reflector and thermal loss in solar still, steam line, and condenser are determined. A solar distillation system of peppermint plants is also subjected to thermal energetic and exergetic study. Exergy and optical efficiencies are 27.58% and 52.25%, respectively, with an average irradiance of 970.5 W/m^2 and 6 kg of peppermint for 4 h. Thermal efficiency of solar still, steam line, and condenser are 95.90%, 95.68%, and 87.96%, respectively. Efficiency of system and oil yield per unit of energy consumed is 41.98% and 6.24 ml/kWh, respectively, without insulating steam line. System's efficiency is 46.36%, with an improvement of 2.67% in energy gain by insulating the steam line. Thermodynamic analysis of developed solar steam distillation system (SSDS) for PO extraction will help in finding out energy saving potential at various parts of distillation unit and in improving the performance of distillation unit. This research would provide energy conservation opportunities in various parts of PO extraction SSDS. Exergy analysis and detailed investigation of condenser and steam line are also performed. As a result, incorporating solar energy into PO extraction technology improves opportunities for the source of income in rural areas and increases both income and level of food security for farmers.

Practical applications

This research would provide energy conservation opportunities in various parts of peppermint oil (PO) extraction solar steam distillation system. Exergy analysis and detailed investigation of condenser and steam line are also performed. As a result, incorporating solar energy into PO extraction technology improves opportunities for the source of income in rural areas and increases both income and level of food security for farmers.

Novelty Statement: Mentioned literature includes thermodynamic analysis of oil extraction system available for crops such as rosemary leaves, basil leaves, etc. Thermodynamic analysis of such a system is limited to these crops and applied to other crops like peppermint, eucalyptus, lavender, etc. As these crops possess different chemical properties and have large potential in essential oil market, a comprehensive thermal analysis is needed to identify various thermodynamic parameters to extract peppermint oil (PO) using solar-assisted steam distillation system. Present work aims to identify energy and power loss due to convection and radiation at different parts of a

Abbreviations: SD, Steam distillation system; SSDS, Solar steam distillation system.

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Review on essential oil extraction from aromatic and medicinal plants: Techniques, performance and economic analysis

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A R T I C L E I N F O

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A B S T R A C T

Essential oils extracted from herbal plants have many foods, cosmetic and medical industries applications. Present study discussed various conventional extraction techniques (steam distillation, hydro-distillation, hydro diffusion and solvent extraction) and advanced (non-conventional) extraction techniques (solvent free microwave extraction, subcritical extraction liquid and supercritical fluid extraction). Economic analysis, kinetics modelling, and GC-MS analysis of essential oil produced by various extraction techniques have also been presented. India is the biggest producer of Indian basil oil and Japanese peppermint oil, and USA is the major importer and exporter of EOs with 14% (US$390.9 m) of world imports and 17% (US$351.7 m) of world exports. Production cost for Steam distillation, Water distillation, solvent extraction and Supercritical fluid extraction varies from 15.85 - 76.50US$/kg, 7.05-86.4US$/kg, 8.35-8.53US$/kg and 6.71-42.69US$/kg, respectively. Second order model are consistent with experimental data as determination coefficient (R^2) is higher than first order model. Non-conventional extraction methods are superior to conventional extraction methods in terms of low cost, time and energy saving, less solvent requirements, shorter extraction time, etc. From the techno-economic and environmental perspective, water distillation with full energy integration is the best method for rosemary oil. In contrast, supercritical fluid extraction is the best method for oregano oil.

1. Introduction

European Pharmacopeia 7th edition (Asbahani et al., 2015) defines essential oils as "aromatic products with a mixture of compounds derived from plant raw material, either separated by steam, dry distillation, or by a suitable mechanical technique without heating." Essential oil is separated from liquid phase without changing its chemical composition by physical method. Herbal plants are very important as most of the population depends on products of these plants (essential oils). The products of these plants are used in food, cosmetic items and medical field etc. (Kant and Kumar, 2021). Various extraction techniques are used for essential oil (EO) extraction from several parts of medicinal plants, such as barks, peels, leaves, buds, seeds, flowers etc. (Tongnuanchan and Benjakul, 2014). The methods used to extract essential oil from these plants are; steam distillation (SD), solvent-assisted extraction, hydro distillation (HD), ultrasonic-assisted extraction, supercritical fluid extraction and solvent-free microwave extraction (Belhachat et al., 2018). Oil extraction techniques are classified as shown in Fig. 1. Conventional methods of essential oil extraction have lower yield and efficiency and higher extraction time than non-conventional methods such as microwave-assisted extraction and ultrasonic-assisted extraction. However, they are still used for essential oil extraction nowadays. Non-conventional methods produce higher yield,

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Process optimization of conventional steam distillation system for peppermint oil extraction

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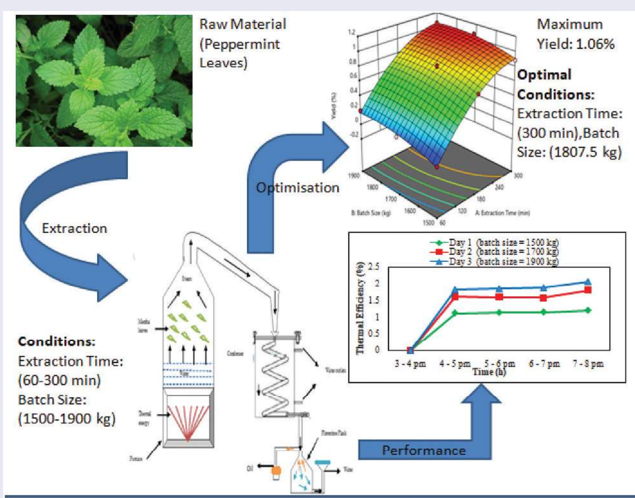
ABSTRACT

This study aims to optimize peppermint oil extraction process using response surface methodology (RSM). Experiments were performed for different batch sizes (1500, 1700, and 1900 kg). System performance was evaluated in terms of thermal efficiency, productivity, essential oil yield (EOY), extraction efficiency, and CO_2 emissions. Total energy consumption for 1500, 1700, and 1900 kg batch sizes are 1379.46, 1336.58, and 1286.56 kWh, while CO_2 emissions are 1104, 1069, and 1028 kg, respectively. Maximum hourly system productivity, cumulative productivity, maximum hourly thermal efficiency, maximum extraction efficiency, and maximum EOY were obtained as 8.3 L/h, 20 L, 2%, 41.5%, and 0.461% (w/w), respectively, for 1900 kg. Average increase in total productivity, extraction efficiency, and EOY was 49.25%, 1%, and 26%, increasing in batch size from 1500 kg to 1900 kg. Extraction time and batch size have important effect ($p < 0.001$) on the extraction yield. Optimal process parameters are identified 300 min of extraction time and 1807.5 kg of batch size. The highest oil yield was 1.0614% under optimal conditions. Experiment was further performed for 1807.5 kg of batch size and the yield was found as 1.04621. Predicted and experimental results were found in good consistency with percentage deviation of 1.436. Therefore, this is helpful in conducting further research on optimizing process parameters for conventional distillation system of peppermint oil extraction.



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Empirical Relation to Predict Essential Oil Yield in Conventional Distillation System

Ravi Kant[1], Anil Kumar[2,*]

Abstract

Peppermint is medicinal herb, and its extracts (essential oils) are of great importance because they are used in pharmaceutical, food, and cosmetic items. Moreover, peppermint oil is also used as anti-cancer, anti-bacterial, anti-viral, spasmodic, anti-diabetic, ulcer healing, anti-obesity, etc. Steam distillation method is used to extract essential oil from peppermint. Boiler, extraction unit, condenser and Florentine flask are the main components of steam distillation system. The objective of present study is to develop a linear relationship for predicting peppermint essential oil yield using a regression model. Peppermint batch size was used as an input variable in linear regression model based on simple correlation analysis. Furthermore, operational performance parameters such as productivity and essential oil yield are determined in this study. Experiments were performed for different batch sizes of peppermint (1000 to 2000 kg) for 5 days. Higher productivity and essential oil yield are obtained for higher batch sizes of peppermint. Productivity and EOY increased from 9 to 19 kg and 0.9 to 0.94% (w/w) with increasing batch size from 1000 to 2000 kg, respectively. Results showed that linear relation of batch size of peppermint with yield was obtained based on the performance of Pearson's coefficient and regression coefficient (Adj-R^2). Pearson coefficient and Adj-R^2 were obtained as 0.99516 and 0.99016. The Pearson and regression coefficient values show that the regression model provided a better correlated output for yield of peppermint. Developed empirical relation provides a powerful tool for investigating the relationship between essential oil yield (output variable) and batch size of peppermint (input variable).

INTRODUCTION

Most of the people worldwide (80%) use herbal remedies to treat their health problems. The extract of aromatic and medicinal plants is used to produce herbal medications. According to records kept by the WHO, some 21000 species are used as medicinal plants. Distillation is used to extract essential oils from medicinal plants [1–3]. Essential oils are utilised as a flavour in food industry, as a scent in cosmetic industry, and in medicine for functional purposes [3, 4]. Peppermint (*Mentha peperita* L) belongs to *Lamiaceae* (*Labiatae*) family of medicinal herbs that grows in the summer and rainy seasons. It is a native species of Mediterranean region that is grown worldwide for flavouring, aroma, medicinal, and pharmaceutical applications [5]. It is commonly used to treat digestive disorders and neurological systems. Peppermint is grown in areas where the soil has a lot of water storage capacity. Underground rootstocks, produced by existing plants are used to grow all commercial peppermint varieties. The rootstocks are formed up of plants that already exist. Rootstock cannot be stored for more than a few days due to quick deterioration due to heat and dryness [6]. Menthone and menthol are peppermint oil's (PO) two main components. Its chemical composition changes according to the location, plant growth, and processing conditions [7]. Figure 1 represents

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