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Original Research Article

Design and development of geothermal-based cooling system for human comfort

Gordhan Das Valasai*[1] | Abdul Waheed Mahar[1] | Muhammad Nawaz Chandio[1] | Abdul Azeem Kumbhar[1] | Atique U Rehman Qureshi[1] | Shauad Ahmed Shaikh[1] | Stefano Landini[2]

1. Department of Mechanical Engineering, Quaid-e-Awam University Engineering Science and Technology, Nawabshah, Sindh, Pakistan.
2. School of Engineering, Mathematics and Physics, University of East Anglia, Norwich, United Kingdom.

*Corresponding Author Email: valasai@quest.edu.pk

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Abstract:
In this study, a geothermal cooling system is developed to address extreme heat conditions in regions like Nawabshah, Pakistan, by utilising the earth's stable underground temperature. This system uses ground-source cooling, powered by a 12V solar PV system or battery, as a low-energy alternative for areas with a limited electricity supply. The experiment demonstrates that a geothermal cooling system could help redress indoor temperatures by up to 16°C during peak summer, resulting in a lower grid-connected or fossil fuel-based cooling system requirement. The results obtained through this study suggest a significant reduction in indoor temperature, ultimately enhancing comfort levels and reducing the reliance on conventional cooling systems like air conditioning. Moreover, the system design is easily adaptable to other regions with similar climates, highlighting its potential for widespread use. However, pipe configuration optimisation is needed to minimise costs and maximise heat transfer rate. This research emphasises geothermal technologies' potential as a cost-effective cooling system, ultimately reducing carbon emissions and improving energy efficiency.

Keywords: Geothermal cooling system, Renewable energy, Sustainable climate control, Indoor temperature regulation, Energy efficiency, Carbon emissions, Energy mix.

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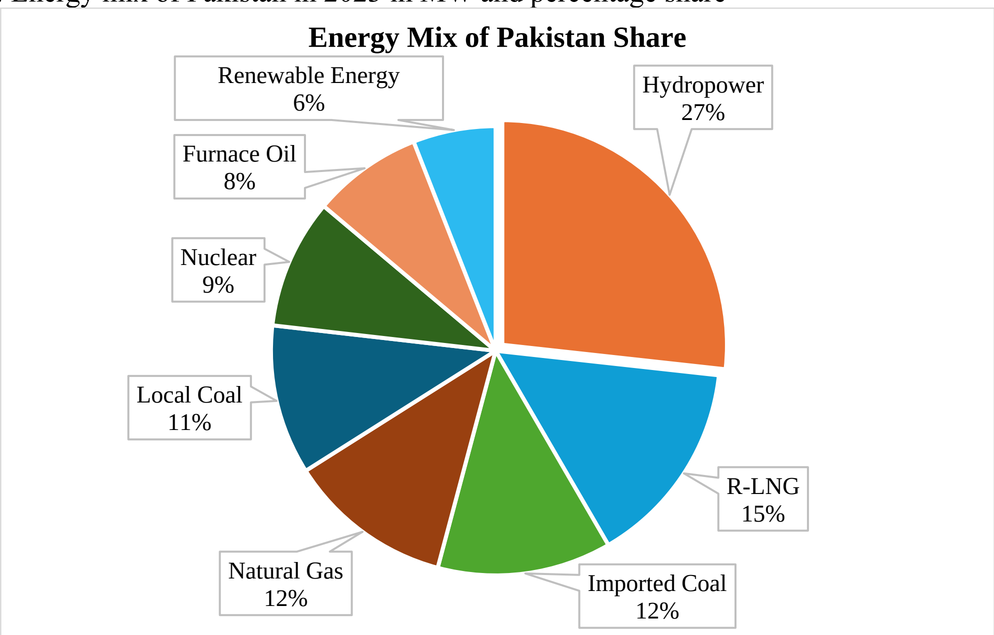
1. Introduction

Energy is a fundamental component of modern society, powering homes, industries, and transportation systems while driving economic growth. The increasing global demand for energy has created immense challenges, with traditional energy sources such as coal, oil, and natural gas facing issues of depletion and environmental harm (Billah *et al.*, 2023; Omer, 2008). As the world transitions to a more sustainable future, the significance of energy becomes even more apparent. In developing countries like Pakistan, energy shortages are a serious concern, with frequent power outages disrupting daily life, economic activities, and industrial production (Shahbaz, 2015; Valasai *et al.*, 2017). Therefore, the exploration and development of alternative energy sources are critical for achieving long-term energy security and environmental sustainability.

Pakistan has been facing issues with electricity shortages for several decades. The country's total installed capacity generation capacity has reached 43700 MW (Shaikh, 2023), with peak demand reaching around 30000 MW during the summer (Khan *et al.*, 2020). However, the actual production is much lower than the designed capacity due to inefficient management, maintenance issues, fuel shortages and financial constraints (Bakht *et al.*, 2022). The gap between supply and demand is around 4000 to 7000 MW, resulting in frequent electricity load shedding and power outages (Anwar & Saeed, 2023). The country faces electricity load shedding, which affects industrial production, the economy and overall quality of life on a large scale. The increasing gap between supply and demand of electricity is due to factors like poor infrastructure, old-age power plants, financial mismanagement at several levels, and heavy reliance on fossil fuels in electricity generation (Khalid *et al.*, 2023). On the one hand, the electricity production from oil and gas is subjected to heavy fluctuations in import prices; on the other hand, indigenous wind, solar, and geothermal energy sources are under-utilised. Currently, the contribution of renewable energy sources to the country's total electricity generation is approximately 6%, defining a significant room for expansion, as shown in Figure 1 (Raza & Cucculelli, 2024).

Figure 1: Energy mix of Pakistan in 2023 in MW and percentage share



This electricity crisis in Pakistan is further complicated by the impacts of climate change, which have introduced extreme weather conditions like heat waves. The province of Sindh, particularly the city of Nawabshah, is known for its harsh summers, where temperatures frequently exceed 45°C, making human comfort and energy supply a pressing concern, as shown in Table-1. On April 30, 2018, Nawabshah recorded an exceptionally high temperature of 50.2 degrees Celsius (122.3 degrees Fahrenheit), marking one of the highest temperatures ever documented in the month of April (Jazeera, 2018).

Prolonged heatwaves pose severe risks to public health, including heat strokes, dehydration, and deaths, as evidenced in 2015 when over 700 people died in Karachi due to a heatwave (Kamal, 2022). Extreme temperatures drive up electricity demand as residents rely on air conditioners and fans, further straining an already overburdened power grid (Salam *et al.*, 2024).

Table-1: Climate of Nawabshah as of 13 June 2010

Temp/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
High °C	33.7	38	44.5	48.5	51	50.5	47.5	48.9	44.5	43	41	35	51
Average High °C	24.3	27.5	33.6	39.6	43.4	43.6	40.3	38.8	38.7	37.4	31.9	25.8	35.4
Average Low °C	6.1	8.8	14.3	19.7	24.6	27.5	27.4	26.1	23.3	18.4	12.3	7.8	18
Low °C	-2.6	-3.6	3	7	15	17	20	18.9	14.6	7.5	2.8	-1	-3.6

Source: Anwar and Saeed (2023)

Given these circumstances, alternative energy solutions have become essential. Renewable energy sources like geothermal, wind, and solar offer promising alternatives to fossil fuels, providing cleaner and more sustainable options for electricity generation (Salam *et al.*, 2023; Salam *et al.*, 2020). The potential of geothermal energy has led to attention due to the increasing need for consistent alternative cooling solutions. The geothermal cooling system utilises the earth's stable inner temperature at a depth of 10-20 feet, under specified conditions and locations. The geothermal cooling system uses earth's energy directly or indirectly and offers a reliable and cost-effective method of indoor temperature reduction.

Pakistan faces several challenges in its electricity supply, including regular power outages and heavy reliance on fossil fuels. Rural areas like Nawabshah, often bear the brunt of these issues. With a limited supply of reliable electricity, a conventional cooling system like air-conditioning seems very difficult to manage. There is a desperate need for an efficient, cost-effective, and sustainable solution in the rural environment.

This study provides a solution to the rural areas by providing a geothermal cooling system suitable for Nawabshah's hot climate to improve human comfort levels. The systems aim to contribute to an increased share of renewable energy in the country's total energy system and enhance the energy security, reducing carbon emissions and providing sustainable technologies.

The current energy crisis in Pakistan needs an urgent call for innovative and sustainable solutions on the part of the government. Under this criterion, the use of geothermal energy as an alternative cooling system offers a promising, viable and energy-efficient option for addressing human comfort.

2. Literature review

The geothermal energy has gained considerable attention as a sustainable alternative to fossil-fuelled energy systems. The expansion of geothermal energy is mainly due to its environmental benefits, cost-effectiveness, and efficiency compared to traditional energy systems. The literature review showcases the feasibility of the systems throughout the world. It adapts like a solution in Pakistan, which faces climatic challenges like extreme temperatures throughout the summer.

The literature review suggests that geothermal systems have been implemented in different countries, demonstrating the feasibility and efficiency of the system through various climatic conditions. The United States, Iceland, and New Zealand are leaders in geothermal energy use, particularly for electricity generation and heating. The United States has a vast potential for geothermal energy. Iceland, which sits atop geothermal hot spots, has utilised this resource extensively, with approximately 90% of homes heated using geothermal energy (Ragnarisson *et al.*, 2018). Similarly, in the EU, several countries like Italy, Sweden, Germany, and Switzerland have adopted geothermal energy systems on a large-scale using Ground Source Heat Pumps (GSHPs).

The research conducted by Rybach and Sanner (2000) highlights that GSHPs are not only a sustainable option for residential and industrial applications but also provide savings of energy to 70% as compared with traditional cooling and heating systems. Similarly, several Asian countries like the Philippines and Japan have also implemented GSPHs systems despite of limited geothermal resources for heating and cooling purposes, especially in urban areas where reducing carbon emissions is a priority.

Table-2: Countries with the highest number of geothermal heat pumps as of 2004

Country	Installed thermal Capacity (MW)	Annual energy use (GWH)	Number of GHP Installations
US	6300	6300	600,000
Sweden	2000	8000	200,000
Germany	560	840	40,000
Switzerland	440	660	25,000
Canada	435	300	36,000
Australia	275	370	23,000

Source: Naqash and Farooq (2024)

In the case of Pakistan, the geothermal energy potential is unique since extreme heat conditions prevail in most regions of the country, mainly in summer. The summer months result in higher demand for electricity in the country due to increased use of cooling through the air-conditioners, but due to over-reliance on fossil fuel-based electricity generation and several other factors fail to meet the increased demand and result in more load shedding than ever before (Usman *et al.*, 2024).

The proper solution to peak summers, geothermal energy as a climate control solution in Pakistan, assures that the demand will be met. Using geothermal energy provides a suitable solution to climatic conditions by giving human comfort. GSHP provides both cooling in the summer and heating in winter. The research carried out in the past shows that GSHPs are 50%

more efficient than conventional cooling systems, making them a viable choice for regions with extreme temperatures (Schibuola *et al.*, 2013).

The geothermal energy systems do not only have lower operational costs, though the initial cost may be a little higher than the conventional systems. However, studies indicate that geothermal systems can compensate for the expenses within a few years. A feasibility study in Turkey has shown that geothermal heat pumps are economically beneficial over most conventional methods except natural gas, as they incur lesser operational costs (Toklu *et al.*, 2010). Similarly, using geothermal energy and other renewable energy sources for power generation can provide a sustainable and zero-emission energy system along with its cost-effectiveness (Salam *et al.*, 2024).

The renewable energy resources in Pakistan are primarily untapped geothermal energy. According to the PCRET, there is great potential for geothermal energy in Pakistan, particularly in areas like Balochistan, where geothermal reservoirs have been identified (Habib *et al.*, 2021). Geothermal systems in Pakistan are still in the very early stages, and little research and investment are found in the sector.

Integrating geothermal systems in Pakistan can help serve as a sustainable solution to solving the country's energy and climate issues. Pakistan is currently using fossil fuels for electricity generation, which has led to regular cases of energy shortages besides pollution. Geothermal systems, particularly ground-source heat pumps, decrease the requirement of conventional air conditioner and heater systems that contribute to a lot of emissions and energy consumption in the atmosphere.

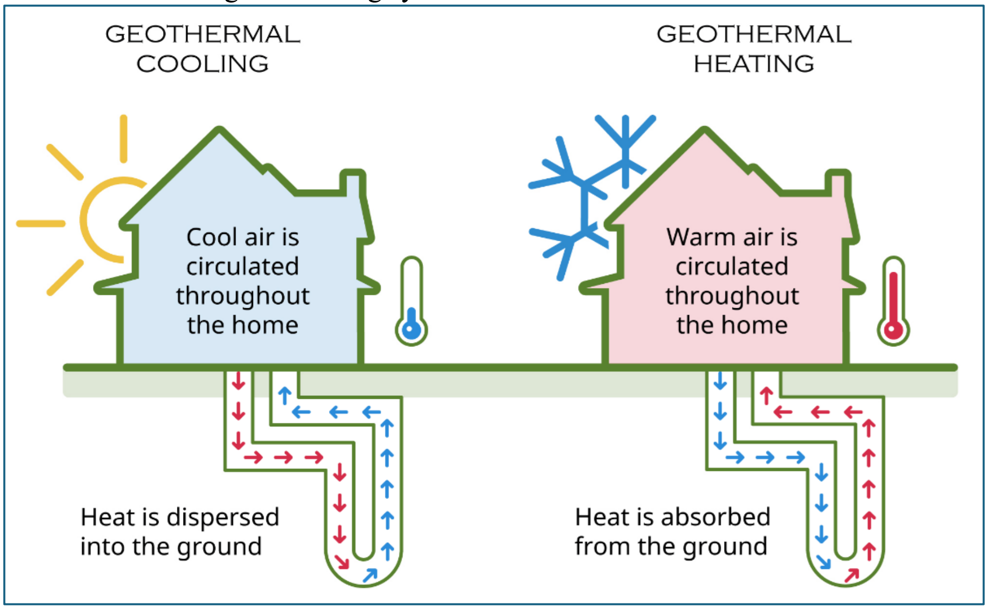
In addition, geothermal energy meets Pakistan's need for low-maintenance, long-lasting energy. Geothermal energy does not depend upon weather patterns like solar or wind energy, thus providing energy year-round. This makes geothermal energy highly suitable in areas like Nawabshah, where temperatures sometimes are extreme, requiring continuous climate control systems. Therefore, as research conducted by Naqash and Farooq (2024) shows that geothermal systems can be operated without much maintenance for decades. Hence, geothermal systems provide a long-term solution for Pakistan's energy crisis.

Globally, the geothermal systems work out to be technically feasible and effective alternatives towards traditional energy sources. More importantly, they have huge benefits in terms of energy efficiency and environmental sustainability. Pakistani context is not different - it has been seriously impacted by extreme heat, and during an unfolding energy crisis, geothermal systems have offered a promising direction. Therefore, ground-source heat pumps may become a green, cost-effective means for indoor temperature control and reduce the burden of Pakistan's national grid and carbon emissions. Research and investment need more effort to explore and implement geothermal energy in Pakistan. With this unrealised potential, Pakistan surely can take gigantic steps to achieve its energy needs and security with reduced impacts of climate change.

3. Methodology

The methodology for this project revolves around the design, development, and implementation of a geothermal-based cooling system for human comfort in Nawabshah, Pakistan. The system leverages the earth's stable underground temperature to provide cooling in summer. This section outlines the materials used, the step-by-step implementation process, and the system's overall design as shown in Figure-2.

Figure 2: Geothermal cooling and heating systems



Source: https://www.cogeothermal.com/green-heat/

3.1. System components

The following materials were used in the development of the geothermal system, as shown in Table-3:

- Blower fan (DC): 12V blower fan for circulating air through the system.
- PVC pipe: The air passage is created by 26 feet (7.92 m) of PVC pipe with a diameter of 1 inch (2.54 cm).
- Insulation: 20 feet (6.09 m) of insulation material to reduce heat exchange between the pipes and surrounding soil.
- Copper pipe: 12 feet (3.65 m) of copper pipe with a ¾ inch diameter, used as the core element for heat exchange between the air and the ground.
- DC power supply: A 12V power supply to run the blower fan.
- Adhesive material: Silicone and tape for sealing connections between pipes and components.
- Connectors: Round 90-degree angled connectors and 180-degree straight connectors for linking pipes.
- Miscellaneous: Tools for digging, securing pipes, and testing the system.

Table-3: Shows the required components for the project

Component	Specifications	
Blower Fan (DC)	12 Volt	-
PVC Pipe	26 ft length	1 Inch diameter
Insulation	20 ft length	-
Copper Pipe	12 ft length	¾ inch diameter
DC Power supply	12 Volt	-
Adhesive Material	Silicon	Tape
Connectors	Round angled at 90°	180° (Straight)

3.2. Installation steps

The installation considered are as follows.

- Site selection: The project was implemented at a hostel room in Nawabshah (Figure 4), known for its extreme summer heat. The location was chosen based on its high temperature, which can exceed 45°C, making it an ideal test site for a geothermal cooling system.
- Pit digging: A pit approximately 10 feet deep was dug just behind the room, 8 feet away from the building. This pit was necessary to house the copper pipe loop that would interact with the underground temperature. The depth was chosen to ensure that the pipes are far enough underground to benefit from the earth's stable temperature range (15-25°C). Shows the dug pit and the copper pipe loop, which is the foundation of the system's heat exchange process.
- Copper pipe loop installation: A loop of copper pipe was placed at the bottom of the pit. This loop serves as the main component for absorbing or dissipating heat between the air and the ground. The copper pipe is connected to PVC pipes that extend from the loop to the blower fan and the room's interior. Figure 4 shows the copper pipe coil connected with the inlet and outlet pipes. This arrangement allows air to be circulated quite effectively through the system.
- Connecting pipes: Both the ends of the copper pipe loop were joined to PVC pipes. One was attached to the blower fan, and the other end extended inside the room. The blower fan, powered by the DC power supply, sucks in air from the room and pushes it through the copper pipes buried in the ground. The air cools down or heats up as it passes through the pipes depending on the season.
- Blower fan setup: The blower fan fitted outside, and it used the PVC pipes to pipe the connection to the loop of the copper pipe here. The fan sucks up the air from the ambient atmosphere, passes it beneath the ground, and thus delivers the chilled or heated air inside the indoor surrounding. Figure 3 the exterior view with the plunged PVC pipes into the underground. It also shows there the blower fan with which the system is supported.
- System testing and adjustments: After the installation, it was tested to know how it would cool the room. The length and diameter of the pipes were modified to maximise heat transfer. The system was checked for leaks and pressure drops so that it could serve with minimal losses. Figure 5 depicts the inner view inside the room where the delivered air has passed through underground pipes after being circulated around them.

Figure 3: 10 feet deep pit, copper loop pipe with inlet and outlet

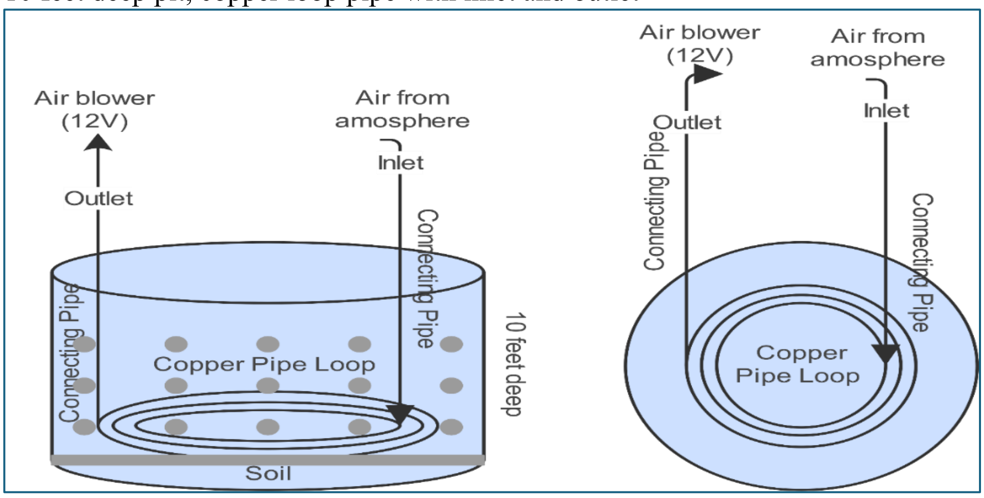


Figure 4: Location of the study (Nawabshah, Pakistan) map

3.3. System design

This is a ground-source heat exchange system. The system's operation draws air through pipes buried deep into the ground, which are constantly at a temperature irrespective of the season. During summer, the system takes the warm air from the room and passes it through buried pipes, where it gives its heat to the cooler ground. The cooled air then returns to the room and maintains a comfortable indoor climate.

It is reversed during the winter months. In winter, cool air from the room is extracted, heated by stable underground earth temperatures, and returned to the room. In this way, the device controls temperature all year without consuming more energy than conventional systems that use heavy air-conditioning systems.

3.4. Key design considerations

The geothermal-based cooling system for human comfort and developed for this study effectively demonstrates the feasibility of natural thermal energy available on earth to be utilised for cooling purposes. The materials and design considerations permit the replication of the system in other regions with similar climates. This system uses the stable temperature of the earth in its underground, which will ensure a sustainable, low-energy solution to extreme heat conditions in Nawabshah, Sindh province and other similar regions in Pakistan. It has great potential for widespread application throughout Pakistan as a sustainable, cost-effective solution to the Pakistan's energy and climate issues. Some of the key design considerations as listed below.

- Pipe layout: The copper pipes are arranged in a horizontal loop at the bottom of the pit to maximise the surface area in contact with the cooler ground, enhancing the heat transfer process. Horizontal loops are more effective in this region compared to vertical ones, as they provide more consistent temperature regulation.

- System operation: The system operates on a 12V DC power supply, which can be powered by solar photovoltaic (PV) cells or a battery.
- Leak prevention: Proper installation of pipes and connectors was critical to avoid leakage. High-quality materials, such as silicone and specialised connectors, were used to ensure airtight seals at all joints and connection points.

4. Results and discussion

The objective of the research was to design a geothermal-based cooling system for human comfort applications and examine its potential for use in hot climates, such as Nawabshah summer in Pakistan. It assesses the effectiveness of cooling, saves money, and determines the feasibility of using energy based on temperature and expenditure data. In this subsection, findings on temperature regulation and costs for individual components that are extracted from Table-4.

4.1. System temperature regulation and efficiency

The primary goal of this geothermal cooling system was to utilise the earth's stable underground temperature to provide consistent cooling. During testing, outdoor temperatures frequently exceeded 45°C, necessitating an efficient cooling solution to maintain indoor comfort. Table-4 presents temperature data measured at the system's suction and outlet points, providing insight into the system's cooling efficiency over different days.

The data in Table-4 indicates that the system consistently achieved temperature reductions ranging from 6°C to 11°C, depending on peak outdoor conditions. For instance, on serials 1 and 2, the temperature decreased from 45°C to 39°C and 37°C, respectively. Serial numbers 14 and 15 showed the largest reductions, with indoor temperatures reduced from 43°C to 32°C, illustrating the system's peak efficiency under sustained operation.

Table-4: Temperature measured at suction and outlet of the system

S. No.	Suction Temperature T_1 (ºC)	Temperature at outlet T_2 (°C)	Difference (T_1-T_2) °C
1	45	39	6
2	45	37	8
3	44	36	8
4	44	35	11
5	43	34	9
6	43	34	9
7	44	34	10
8	45	34	11
9	43	34	9
10	42	34	8
11	44	34	10
12	43	34	9
13	45	34	11
14	43	32	11
15	43	32	11

4.2. Extended efficiency analysis with depth variation

Further analysis revealed that increasing the depth of the buried copper pipes (from 10 feet to 15 feet) contributed to more consistent cooling efficiency throughout the day, particularly in the hottest hours. This finding suggests that depth selection plays a crucial role in maximising the system's cooling capacity by taking advantage of the cooler, stable sub-surface temperatures. This aspect is especially important in regions with similar climatic challenges, where extreme heat demands robust cooling solutions.

4.3. Energy consumption and cost efficiency

It relies on a low-energy 12V DC blower fan, making it operational at minimum energy usage. The fan could be powered either by solar PV cells or by a small battery, hence suited for use in areas with little or no electricity supply. It drew significantly less power than the conventional air conditioning units, which would mean a considerable amount of savings in energy consumption.

Figure 5: Change in temperature at inlet and outlet

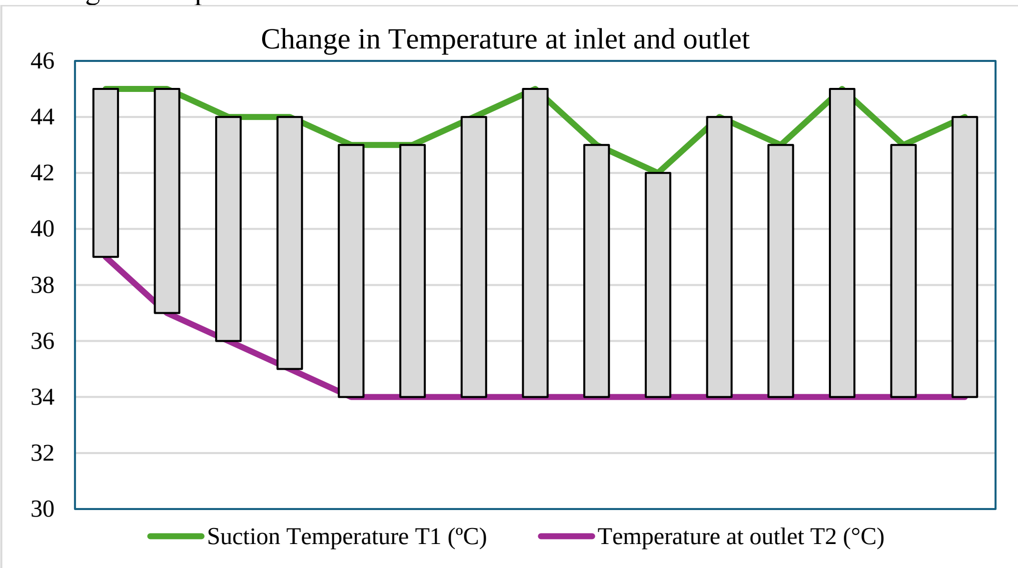


Table-5: Cost of the different components used in the system

Component	Price		
	(PKR)	(USD)	(GBP)
Blower	10,000	34	27
Copper Pipe	5,000	17	13.5
PVC Pipe	2,000	6.8	5.4
Insulation	1,500	5.1	4.05
DC Supply (12V)	4,500	15.3	12.15
DC Wire	500	1.7	1.35
Connectors	500	1.7	1.35
Adhesive Materials	1,000	3.4	2.7
Total	25,000	85	67.5

Table-5 below presents the costs associated with each component, highlighting the financial feasibility of the system for broader applications. The total cost of instalment of the system 25,000 PKR was feasible as estimated investment with a payback short period of 3 - 4 years considering expenditures of local cooling. Thereby, along with possible long-term operation cost efficiency, the above aspects portray the system as one low in cost and sustainable source for alternative cooling in distant and untapped regions.

4.4. Performance over extended periods

Tests conducted over a 24-hour period demonstrated that the system maintained cooling efficiency even as outdoor temperatures fluctuated. During nighttime, when outdoor temperatures dropped, the system continued to provide stable cooling with minimal additional power, enhancing its cost-effectiveness for households or small commercial settings. Despite varying outdoor conditions, the consistent indoor temperature control reflects the system's adaptability for off-grid applications, particularly in energy-scarce regions.

4.5. Limitations and scope for improvement

Despite its success, there are significant limitations that must be discussed. The performance of this system was evaluated mainly for one climatic region known as Nawabshah that is likely to have limited this investigation's generalisation to another kind of climate. Testing this system in various geographical locations across different soil compositions and varying climatic conditions would give a more comprehensive notion of the systems' adaptability.

In addition, although this system had cooled efficiently at low cost, future varieties should centre on pipe configurations to increase depth for better heat exchange and should use materials with higher thermal conductivity in place of aluminium.

5. Conclusion

This paper demonstrates that a geothermal cooling system designed for Nawabshah, Pakistan, was feasible and practicable for reducing indoor temperature and saving energy. The use of this stable underground earth temperature of the ground-source heat pump reduced the temperature up to 16°C from peak summer conditions and was able to maintain warmth when winter arrives, thus presenting an alternate sustainable source instead of conventional cooling. This makes for great practical applications, especially in regions with high energy costs and unstable electricity supply. Its low energy consumption, courtesy of renewable power sources such as solar PV cells or batteries, presents a feasible solution to areas that are energy-limited by directly working towards the local challenges while furthering the goals toward global sustainability: away from fossil fuels and reduced carbon emissions.

Future research should continue on the aspects of the system in various soils and climates as well as optimum component materials for enhancing heat exchange while improving the cost-effectiveness of this method. It is worth pursuing further research into geothermal cooling and offering a scalable, sustainable solution applicable to diverse climates that experience similar energy and environmental constraints.

Declaration of conflict of interest

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ORCID iD:

Gordhan Das Valasai	https://orcid.org/0000-0002-0476-4927
Abdul Waheed Mahar	https://orcid.org/0009-0002-8305-7186
Muhammad Nawaz Chandio	https://orcid.org/0009-0008-8348-8537
Abdul Azeem Kumbhar	https://orcid.org/0009-0004-1066-9557
Atique Ur Rehman Qureshi	https://orcid.org/0009-0005-0059-3963
Shauad Ahmed Shaikh	https://orcid.org/0009-0000-5350-821X
Stefano Landini	https://orcid.org/0000-0001-6211-7800

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