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Inspection of dynamic modelling and control of a parabolic trough solar collector

Anubhav Goel [a], Gaurav Manik [a,*], Om Prakash Verma [b]

[a] Department of Polymer and Process Engineering, Indian Institute of Technology Roorkee, India
[b] Department of Instrumentation and Control Engineering, Dr. B R Ambedkar National Institute of Technology Jalandhar, India

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ABSTRACT

Solar energy conversion to thermal energy has enormous potential for meeting the need for heat energy in a variety of applications. A parabolic trough solar collector (PTSC) has proven to be effective in solar to thermal conversion. Installing a PTSC to service a specific application necessitates a large setup and significant cost, so it would be beneficial if such system analytically tested and optimized beforehand. As a result, the study relating to finding the options that might assist in improving the PTSC performance becomes critical. Modelling the PTSC is one such useful way that can assess it and suggest possible changes. Thus, surveying the literature in this area becomes equally important. This study attempts to explore the potential of dynamic modelling of PTSC's and its control mechanisms. A summary of the prospects for PTSC dynamic modelling is offered, a simplified basis is given to reader by covering the fundamentals of modelling methodologies, as well as the associated research that go along with them. Further, PTSC control components and improvements are investigated. Relevant discussion about the possibilities and limitations are provided, future scopes are also included.

Selection and peer-review under responsibility of the scientific committee of the 3rd International Congress on Mechanical and Systems Engineering.

1. Introduction

Solar energy exploitation and conversion on a big scale is seen as the long-term, sustainable, and prime option for attaining global justice and meeting the world's increasing energy demand. Concentrated solar power (CSP) and photovoltaic (PV) are two promising methods for generating electricity from the sun's energy that are now accessible. PV suffers from the problem of difficult electronic disposal and has only electrical output. Though, CSP can aid the power generation as well as can fulfil thermal energy requirements [1]. Currently, parabolic trough solar collectors (PTSCs) are the most mature among the CSP options [2]. Plants/processes based on the PTSC are a great alternative for long-term power supply because they can produce 100 percent renewable energy.

PTSC converts solar energy to heat energy and uses a parabolic-shaped reflective mirror that converges solar irradiation falling onto its surface towards its focal line, Fig. 1. An absorptive pipe, also known as heat collector element (HCE) or absorber, is located at the focal line of the mirror. It consists of a metallic absorber enclosed in a glass envelope, the annulus space between the two is vacuumed to reduce the heat losses. It absorbs the solar radiation incident on it and transfers this heat energy to the heat transfer fluid (HTF) flowing through it [3]. The heat gained by HTF is utilized in applications like power generation, desalination and as a heat source for many industrial processes. If PTSC is appropriately utilized to provide the heat energy requirements of industrial processes by tuning the process conditions and materials, then solar energy can substitute the huge consumption of conventional fuels to provide electricity in industry. Even if confined to heat intensive processes only, there are many processes such as cooking, drying, degreasing, pasteurization and others which are generally driven by fossil fuel-based energy. All these processes require temperatures in the range of 50 to 260 °C for them to run without interruption. PTSCs can proficiently offer to meet the heat requirements of most of these processes [4].

To serve the distinct applications in an appropriate manner it is important that the output of PTSC is maintained at required values. Thus, it is essential to design, study, and look for the possible improvements in the control systems related to PTSC. Further, to

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* Corresponding author.
E-mail addresses: agoel@pe.iitr.ac.in (A. Goel), gaurav.manik@pe.iitr.ac.in (G. Manik), vermaop@nitj.ac.in (O.P. Verma).

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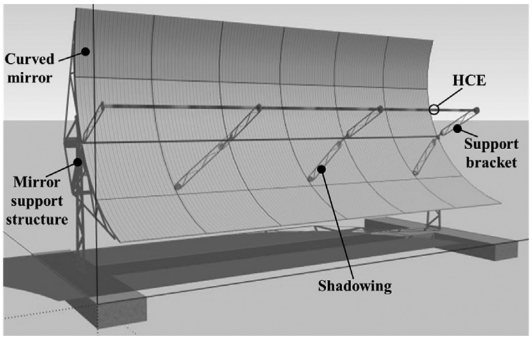

Fig. 1. PTSC and its components [5].

design or improve the control system it is essential to have the knowledge of dynamics of the system. Therefore, designing, testing, and validating automatic control systems for PTSC requires modeling of its dynamic behaviour. Many studies have been carried out to explore the dynamics and control of the PTSC. Such as control of solar energy systems based on PTSC and solar tower was conducted by Camacho et al. [6]. Technologies are outlined along with their current state of development, and the primary issues that solar energy system controllers face are highlighted. Naidoo et al. [7] highlighted that inefficient solar tracking and position management of the collection result in energy losses. Also, developed a control algorithm included in a programmable logic controller to best rotate the PTSC to the desired position with the sun's movement. In another study, Navas et al. [8] have discussed the problems in operating PTSCs under the improper solar radiation and proposed the optimal control strategy while comparing it with the feedforward and a PI controller. Dynamic modelling and simulation of a PTC system having a concrete thermal energy storage and kettle-type boiler is carried out by Sattler et al. [9]. The simulated system is examined to deliver the required saturated steam for a beverage factory.

Besides these specific studies, there are some reviews as well that inspects the problems and possible solutions associated with the dynamic modelling and control of a PTSC. A study by Camacho et al. [10] provides an overview of the various automatic control strategies used to regulate the output temperature of solar plants with CSP collectors. Same authors have also provided a review of the various advanced automatic control techniques used to regulate the outlet temperature [11]. Aurousseau et al. [12] examines the control mechanisms for direct steam generation systems using the line focus CSP (PTSC or linear fresnel reflector). The evaluated control systems have either been proposed in the literature or have been implemented in live plants or prototypes.

The mentioned studies are focused on a specific problem and the review articles have mainly concentrated on the control principles and advancements. So, there is a need of a review article that not just encompasses the control mechanism for PTSC but also explores the possibilities in dynamic modelling. As a result, the conundrum of determining which sort of model to use for assessing the PTSC for a certain application can be avoided. This paper contributes in the following ways to the above-mentioned points:

- Components and advancements in PTSC control are explored.
- An overview of the prospects in dynamic modelling of PTSC are presented.
- Discussion and future scopes of the control and dynamic modelling of PTSC are covered.

In the current paper, an outline about the dynamic modeling and control of PTSC is given in Section 2. The advances covering the modeling techniques are covered by Section 3 while the generally used control strategies are discussed in Section 4. Section 5 concludes with the paper's main conclusions.

2. Dynamic modeling and control of PTSC: An overview

Before learning how to develop the dynamic model of PTSC or its control, it's important to understand the input solar concentration requirements to operate it. Sun rays that reach the earth are classified as diffused irradiance or direct normal irradiance (DNI), as seen in Fig. 2. A portion of sunlight gets scattered by clouds before reaching the earth's surface and is known as diffused irradiation, while another portion reaches the surface directly and is called DNI. A PTSC system operates on the DNI as an input and its quality has an impact on PTSC's performance [13]. If a certain amount of DNI is not fed to the PTSC, the system's output will be nil.

Another important aspect to be remembered is that in most of the processes the heat energy is generated using the fossil fuels and thus the input source can be varied as control variable. Though in PTSC based systems, the input is solar irradiation that cannot be manipulated, also it varies over the day as well as seasonally. So, the input is frequently disturbed while considered for control. To cope with the nonlinearity and uncertainty in PTSC operation, firstly a good model that can capture its dynamics is essential and secondly the generic PID controllers are not enough to deal with the mentioned problems [15]. The implementation of more effective control systems that result in better reactions is necessary to improve the number of PTSC based systems. The thermal process variables are controlled by keeping the major process variables closest to their set points, commonly done in a closed loop.

Along with the aforementioned challenges, few assumptions are also made to devise the dynamic model. Analysis of heat transfers in HCE leads to the heat gain by HTF and thus becomes an important aspect of research. Many modeling studies pertaining to PTSC have focused on it because its performance can speak volumes about the entire system [16]. Modeling of HCE involves the conservation of energy at its surfaces and works with many assumptions that depend upon the kind of model required [17], but there are a few that are generic:

- HTF flow inside the HCE is fully developed
- Geometric features of the PTSC are constant, means they are unaffected by phenomena like thermal expansion.
- Incompressible fluid.
- The sky is thought to be a black body.
- Collector surface provides specular reflection.

Various studies are available in the literature that are based on the assumptions indicated above. For analyzing the performance of PTSC through a model, it is often assumed that it is in a steady state, suggesting that parameters like surface temperatures of HCE or HTF flow rate are constant. In heat transfer evaluations, dealing with steady flow is easier, and several studies are available. Though, the investigations considering the dynamic or transient nature of PTSC operation are relatively few. PTSC systems primarily work in transient situations, treating the flow pattern as transient is more realistic. PTSC cannot work under steady conditions because to the fluctuating nature of environmental factors and sun irradiation. The inclusion of transient flow in a model is tough, but it should be considered when researching or constructing a PTSC model for closeness to a real system. Some of the important studies covering the dynamic modeling and control of PTSC are listed in Table 1.


Direct normal irradiance (DNI)

Diffused irradiance

Fig. 2. Types of solar irradiation [14].

Researchers have employed various software tools and numerical approaches to model the dynamics PTSC and its control, as can be seen in Table-1. Each study included in the table focuses on a different area of PTSC that needs to be investigated and improved.

The main aim of a control system for a PTSC is to keep its outlet temperature at a required value (Set point) irrespective of the disturbances like changes in input solar radiation due to clouds, change in input HTF temperature, and others. As can be ascertained from Fig. 3, the only way to accomplish this is to vary the fluid flow, which means the operation cycle characteristics require that the oil flow change significantly during operation.

This causes large changes in the PTSC dynamic properties, such as response time or delay time, making it difficult to achieve appropriate performance with a fixed parameter controller over the operating range. As a result, PTSC has a number of traits that make it challenging to manage [10], such as:

- In relation to the process's dominant time constant, solar radiation behaves as a quick disruption.
- The delay in action is dependent on the manipulated variable (HTF flow rate). So, the input/output transport delay varies with time.
- There are strong unmodeled dynamics when modelling simplifications are done, and the linearized dynamics vary with the operating point.

Despite the mentioned constraints and challenges, it is important to study and search for possible improvements in the dynamics and control of PTSC because:

- The energy produced using the PTSC is often expensive, therefore any improvements in performance acquired via the application of advanced control techniques would assist to position them as a viable alternative to traditional energy sources.
- PTSC is effectively a very big heat exchanger, and these types of systems are quite often required in many industrial processes. The experience acquired with modelling and control can be applied to industrial processes.

Table 1
Summary of studies on dynamic modeling and control of PTSCs.

Author	Technique/Software Used	Remarks
Eck et al. [18]	Modelica	Dynamic behaviour of the PTSC field studied using a nonlinear simulation. Impact of various shadings of a 1000 m loop are simulated and feed water control systems are examined.
Barcia et al. [19]	Simulink	To optimize and control the HTF temperature in a PTSC based thermoelectric plant, a model is proposed such that the plant's normal operation remains mostly unaffected. Also, model results are compared with real plant data.
Luo et al. [20]	Computer simulation	A mathematical model of PTSC is established and then other pump, heat exchangers, etc. are added to deliver a complete model for solar collector array (SCA). Further, Real-time simulation is used to test dynamic properties under disturbances such as varied irradiation, changed working medium, and so on.
Stuetzle et al. [21]	Computer simulation	Equations considering the transient energy balances of PTSC are given. A model predictive controller is designed and tested for a summer and a winter day. The impact of the control on the plant's gross output is also investigated.
Guo et al. [22]	MATLAB/Simulink	Describes and assesses a new nonlinear dynamic model for a PTSC based field for direct steam generation in recirculation mode. A new generalized predictive control technique is also proposed.
Desideri et al. [23]	Modelica	A dynamic model of PTSC is presented and is validated by comparing the model results with the experimental data collected from Plataforma Solar de Almería, Spain. Both steady state and transient conditions are studied.
Al-Maliki et al. [24]	Advanced Process Simulation Software (APROS)	A detailed dynamic model of PTSC based power plant is proposed with clearly described HTF paths. The advanced control circuits included are drum level, economiser water bypass, attemperator, and steam bypass controllers.
Navas et al. [8]	MATLAB	Problems faced while operating the PTSC arrays during the partial radiation are considered. An optimal control method is given and compared to a traditional one that uses a feedforward and a PI controller to overcome the challenges.
Lima et al. [25]	Computer simulation	Output temperature of PTSC based desalination plant is controlled using the Filtered Dynamic Matrix Control (FDMC). Results from a validated solar plant model are presented for distinct conditions. Comparison of results with nonlinear control techniques is also given.

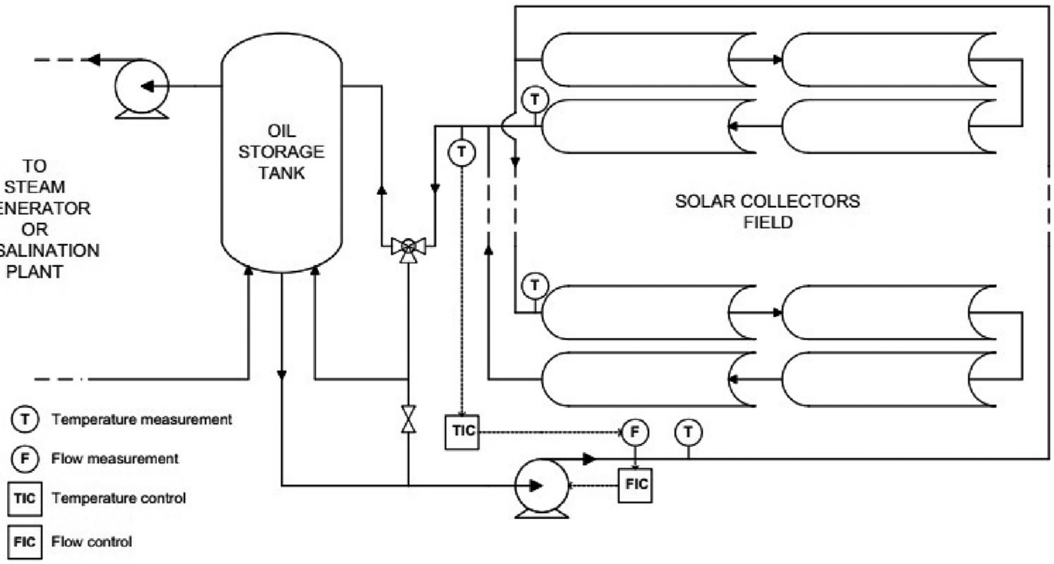

Fig. 3. A schematic showing the control loops.

3. Progress in dynamic modelling and control of PTSC

The analytical model can be used to analyse the system's performance and the impact of various parameters on its efficiency. It provides advantages like reduced time and cost for analysis and the ability to analyse the system's performance on a variety of criteria. In the literature, there are numerous modelling studies that present various dynamic models to analyse the performance of PTSC. The majority of the models are first principle models which means they are based on basic laws of science, for instance based on the energy balance of the system. There is no specific foundation for categorising these models. Nevertheless, the dynamic models proposed for control purpose can be broadly classified into two categories.

3.1. Fundamental models

Under this category the dynamics of the PTSC system is described using the partial differential equations (PDE) obtained by analysing the energy balance. Major point of dynamics to be considered for the control purpose is the HTF flow rate. It is to be noted that in studies pertaining to thermal analysis or heat loss calculations of PTSC, it is ok to consider the HTF flow in steady state [5]. Though, for control purpose it is important that transient behaviour of HTF flow is embedded in the model. Various researchers have used lumped capacitance analysis to account for transient flow in their models [26,27]. Control volumes for HCE are used in this type of analysis, as shown in Fig. 4.

Different sections of the HCE are analyzed at a constant temperature to develop the analytical equations representing the transient behavior of the PTSC using lumped-capacitance analysis. Fig. 4 shows the control volume for analyzing the HCE under transient situations. The energy balance of different sections considered using the control volumes leads to the energy balance equations for transient analysis. The following are the general equations that are employed in this analysis:

$$\left(\rho_f c_f A_f\right)\Delta y \frac{\partial T_f(y,t)}{\partial t} = Q_3(y,t)\Delta y + Q_f(y,t) - Q_f(y+\Delta y,t)\ \ \text{(for HTF)} \tag{1}$$

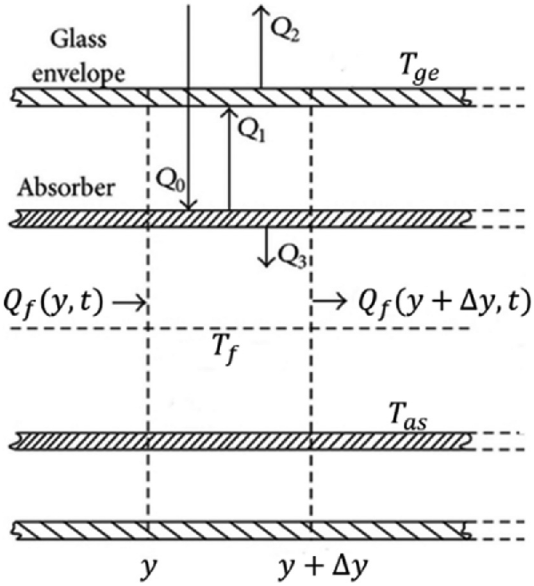

Fig. 4. Lumped capacitance analysis of HCE [27].

$$(\rho_{as} c_{as} A_{as})\Delta y \frac{\partial T_a(y,t)}{\partial t} = Q_0(y,t)\Delta y - Q_1(y,t) - Q_3(y,t)\ \ \text{(for absorber tube)} \tag{2}$$

$$\left(\rho_{ge} c_{ge} A_{ge}\right)\Delta y \frac{\partial T_{ge}(y,t)}{\partial t} = Q_1(y,t) - Q_2(y,t)\ \ \text{(for glass envelope)} \tag{3}$$

Here, Δy represents the small volume of the HCE, $(Q_0, Q_1, Q_2, Q_3, \text{and} Q_f)$ represents the heat transfers at different surfaces of the HCE cross-section, $(T_f, T_{ge}, \text{and} T_a)$ are temperatures at different surfaces of HCE, ρ is density, c is specific heat, and A is area of cross-section. Each equation represents an energy balance at different HCE surfaces and used to evaluated the dynamic behaviour of the system.

Many researchers present dynamic models to consider the system's transient behavior. To analyze a large-scale experimental system, Xu et al. [26] proposed a dynamic model. In another study, a field of PTSCs is examined via the lumped parameter dynamic model presented by Luo et al. [20]. Besides the lumped-capacitance analysis, the dynamic behaviour of HCE is also studied using the 1-D analysis. It means the temperature gradients are studied in only single direction of HCE (generally radially). The equations to represent the transient behaviour 1-D analysis can be given as:

$$(\rho cA)_{htf}\frac{\partial T_{htf}}{\partial t} = -\dot{m}_{htf}\frac{\partial}{\partial t}(cT)_{htf} + Q_{htf}\Delta x \quad \text{(for HTF)} \tag{4}$$

$$(\rho cA)_{a}\frac{\partial T_{a}}{\partial t} = A_a\frac{\partial}{\partial t}(k_a\frac{\partial T_a}{\partial t}) + Q_0 - Q_1 - Q_u \quad \text{(for absorber tube)} \tag{5}$$

$$(\rho cA)_{e}\frac{\partial T_{e}}{\partial t} = A_e\frac{\partial}{\partial t}\left(k_e\frac{\partial T_e}{\partial t}\right) + Q_1 - Q_2 \quad \text{(for glass envelope)} \tag{6}$$

The temperatures of the collector components vary with time in the lumped-capacitance model, but they remain consistent across time. It is less difficult than the 1-D model, which considers temperature variations over time and axial position. The lumped-capacitance model is fast and delivers accurate simulation results. Valuable predictions about the heat losses, HTF temperature, etc., can be made by using it.

3.2. Data-driven models

The data is fed to a machine learning tool (known as black box) in this modelling approach, which establishes a correlation between the input and output. Although this is a new method in the realm of PTSC, it yields satisfactory results. Many studies have used parameter identification to create linear black-box models for control purposes. Several approaches, including various forms of artificial neural networks (ANN), have been developed for developing a nonlinear model of a PTSC system, which has been utilized for simulation or as a core element in various model-based prediction systems [11].

To significantly reduce the computational load to 3 % of the MPC computation time, work by Moreno et al. [28] suggests the employment of artificial neural networks to estimate the optimal flow rate provided by an MPC controller. Using a 30-day synthetic dataset of a collector field managed by MPC, the neural networks were trained. The effects of feeding the network with various numbers of measurements have been studied.

Based on the heat transfer mechanism augmented by artificial neural network, a new hybrid model is suggested by Guo et al. [29]. These two traits apply to this hybrid model.

(1) Using a heat-transfer and hydrodynamic coupling steady-state mechanism model as a prior model, values are acquired that include the mechanism factors, which are then utilised as input to an ANN model.

(2) A back propagation (BP) ANN model with two four-hidden-layer BP networks. To increase the simulation's accuracy, the second four-layer neural network analyses the solar field's outlet temperature after modelling its inlet pressure and outlet temperature in the first network's four layers.

4. Control strategies

The operational time of the PTSC system could be increased by employing efficient control systems that result in better performances. As discussed before the control of a PTSC system has complex dynamics and various other constraints, in such cases simple linear low order models fail to properly approximate the dynamics of the system. Thus, more advanced control techniques are needed as tight control specifications and higher uncertainties are required. Some important control strategies used in relevance PTSC are:

i. *Feedforward control*: feedforward controllers are often utilised to mitigate the effects of external and observable disturbances. Using a model of how the disturbances affect the process, the disturbances are detected and utilised to determine the value of the manipulated variable that must be maintained at the setpoint to retain control [30].
ii. *Cascade control*: in this technique, the control system is divided into two control loops, one is known as a slave and utilized for disturbance compensation, while the other is a master loop that controls the process output. It's a classic control method for cancelling the effects of disturbances on the output [31].
iii. *Model predictive control* (MPC): a model of a system is used to predict the future values of the associated parameters at upcoming time instants. So that the manipulated variable can be adjusted accordingly to retain the desired output [28].
iv. *Internal model control* (IMC): a controller can be utilized in an open loop manner if there are no disturbances and modelling errors. The control so developed with this perception is stable if and only if the process is open loop stable and the controller is stable. To accommodate for uncertainties and disturbances, the feedback signal is added [11].
v. *Adaptive control* (AC): When the process dynamic changes, the main principle underlying AC is to adjust the controller accordingly. Adaptive control can be defined as a type of nonlinear control in which the state variables are divided into two groups and move on two different time scales. The process variables (internal loop) relate to the faster-changing state variables, whereas the slower-changing state components correspond to the estimated process (or controller) parameters [32].
vi. *Nonlinear control* (NC): Explicit recognition and exploitation of plant nonlinearities could improve performance and robust stability, albeit at the cost of increasing controller complexity. Traditional nonlinear control strategies, which involve nonlinear transformations of input or output variables, have been used to make progress in this area [33].

5. Conclusions and future directions

In the preceding sections, a significant number of works on dynamic modeling and control of PTSC have been discussed. Techniques for constructing a dynamic model of the PTSC are described. It can be determined that a significant number of useful and versatile mathematical/software tools for dynamic modeling are accessible. Various strategies have been proposed to control the dynamics and increase the PTSC's efficiency. It's important to remember that even tiny improvements in performance can add up to big savings, especially in large systems.

Various dynamic models for PTSC analysis based on various technological elements are discussed in this article. This gives a better understanding of which model to use to investigate the PTSC, depending on the application. Further, various constraints and complexities that should be kept in mind while aiming to control a PTSC system are discussed. Different control strategies that have been utilized or suggested earlier are described so that the reader can relate and understand.

PTSCs can serve in many applications like power generation, desalination, process heating, etc. However, its share in these is still not much significant. Also, although a significant amount of study has been done in this sector, there is still room for improvement. Many improvements in control of PTSC system are suggested to increase its performance, but due to technological challenges, they are yet to be implemented. The following are some potential future directions for improving PTSCs:

- According to the articles studied, PTSC proficiency can be improved even further if process/design adjustments in control systems recommended through dynamic modeling are implemented in a real-world setting.
- Advanced research methods for analyzing PTSCs, such as machine learning techniques, are yet to be properly tested.
- Modeling methodologies are based on many assumptions. Efforts can be made to reduce them so that future collectors are analytically prepared for the future.

CRediT authorship contribution statement

Anubhav Goel: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Investigation, Validation. **Gaurav Manik:** Supervision, Writing – review & editing. **Om Prakash Verma:** Data curation, Investigation, Writing – review & editing.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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