



RESEARCH ARTICLE

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TRANSIENT THERMAL PERFORMANCE ANALYSIS OF NANOPARTICLE-COATED FLAT PLATE SOLAR COLLECTORS USING MATLAB-BASED MODELING

Juber Khatik^{*1}, Nilesh Salunke², Mujahid Husain³, Yogeshkumar Pathak⁴, Kailas Deore⁵
 Pradeep Solanki⁶ and Pravin Shirule⁷

¹Research Scholar, SSBT's College of Engineering & Technology, Bambhori, Jalgaon, Maharashtra, India

²Principal, SVKM's Institute of Technology, Dhule, Maharashtra, India.

³Professor, SSBT's College of Engineering & Technology, Bambhori, Jalgaon, Maharashtra, India.

^{4,5}Assistant Professor, R. C. Patel Institute of Technology, Shirpur, Maharashtra, India.

^{6,7}Associate Professor, SSBT's College of Engineering & Technology, Bambhori, Jalgaon, Maharashtra, India

¹<https://orcid.org/0000-0003-3550-4367> ²<https://orcid.org/0000-0003-4185-7556> ³<https://orcid.org/0009-0005-7663-6691>

⁴<https://orcid.org/0000-0003-4453-4912> ⁵<https://orcid.org/0000-0002-3229-5902> ⁶<https://orcid.org/0000-0001-8949-9562>

⁷<https://orcid.org/0009-0008-4527-1222>

E-mail: *juber.khatik@rcpit.ac.in, nilesh.salunke@svkm.ac.in, husain.mujahid@SSCOETJalgaon.ac.in, yogesh.pathak@rcpit.ac.in,
kailas.deore@rcpit.ac.in, p_solanki@rediffmail.com, pashirule@gmail.com

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ABSTRACT

Flat plate solar collectors (FPCs) have significant thermal performance that is vital in improving the efficiency of solar thermal energy systems. Traditional absorber coating, including black paint, has limited optical and thermal behavior, and nanomaterial-based absorber coating has received interest in improving performance. The purpose of the study is to assess and compare the thermal performance of FPCs when coated with CuO, Al₂O₃ and graphene nanoparticles. A mathematical model simulator of the performance of the collector under dynamic solar and environmental conditions was created using transient lumped capacitance in MATLAB. The model computes the important thermal performance indicators, such as outlet fluid temperature, useful heat gain, and instantaneous efficiency, and it has been verified against literature data. Simulation findings indicate that nanomaterial coatings are much more efficient in terms of thermal conductivity with graphene showing the most dramatic efficiency improvement of up to 0.835 relative to 0.725 when using black paint and a maximum useful heat gain of 834 W relative to 724 W. Graphene-coated collectors on average increased efficiency by 15.2% and useful heat gain by 13.8%. The improvements of Al₂O₃ and CuO coating were around 9-11% higher than black paint. Such improvements are explained by the high thermal conductivity and optical absorption of nanoparticles. The results show the promise of advanced nanocoatings to enhance the efficiency of solar thermal systems and offer a solid basis to optimize and experimentally validate such systems in the future.



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I. INTRODUCTION

Solar flat plate collector (FPSC) is a widely used solar thermal system that absorbs solar energy and transforms it into heat energy to be used in different ways, such as heating water and heating space. The FPSC consists of the core element, which is the absorber plate that directly affects the thermal efficiency of the system because it absorbs solar radiation and transfers heat to the working fluid [1–4].

The design parameters and material properties of the absorber plate have a considerable influence on the performance of the system. Materials with a high thermal conductivity, including copper and aluminum, increase the efficiency of heat absorption and transfer, which decreases thermal resistance [5] [6]. Also, surface alterations, including roughened surfaces, prolonged surfaces, and selective surface finishes are used to reduce radiative and convective heat losses to enhance heat retention [7] [8]. The geometrical arrangement of the absorber plate, plate thickness, channel structure, and fluid temperature increase are also further affected by the heat transfer efficiency and fluid temperature increase [1–3]. The optimization of these design parameters results in the achievement of high performance of FPSC and the system becomes efficient and effective in real-life applications. The development of absorber plate technology has greatly increased the efficiency of solar flat plate collectors (FPSC) through the enhancement of the mechanisms of heat absorption, retention and transfer. Surface modifications and innovations that include micro-grooved, V-corrugated, and selectively coated surfaces have been proposed to optimize optical absorption and reduce radiative and convective heat losses [1-8]. Absorber plates that have been integrated with nanomaterials, including carbon nanotubes, graphene, and metal oxide coating, have demonstrated increased thermal conductivity and solar energy conversion efficiency [9–11]. Geometric improvements, including the use of serpentine flow paths, spiral tubes, and multi-channel absorber designs, have improved the heat transfer through the increased surface contact between the working fluid and the absorber plate [1-12]. All these developments are aimed at enhancing the overall thermal performance and efficiency of FPSCs, and therefore, they become more suitable to sustainable and high-performance solar energy use. Improvement of solar thermal absorber plates by using different coatings, materials and structural changes is a common study in the quest to enhance efficiency, heat transfer and energy absorption. Coating modifications have shown to have great enhancements in thermal performance. Palanikumar et al. [13] discovered that a 0.1 mm black nickel thin film covering on copper absorber tubes reached a maximum absorptance of 0.98, reducing emissivity and maximizing thermal efficiency to 74.3%. In the same way, Nazari et al. [14] demonstrated that the coating of a cuprous absorber plate with CuO nanoparticles enhanced efficiency by 35.8% and exergy efficiency by 11.2. Coatings based on graphene also provided significant improvements, with Kumar et al. [15] reporting that graphene-doped black paint on a triangular plate solar air heater, and Mariraja et al. [16] reporting that graphene nanoplatelet (GNP) nano paint on solar still absorber plates, both raised thermal efficiency by 4.91 and exergy efficiency by 4.27. Moreover, Han et al. [17] found that the application of 15 wt% silicon (Si) particles to the plate of a solar still absorber increased the surface temperature by 65.81, which maximized the yield of the distillate.

Coatings that are enhanced by nanoparticles have also been widely researched. Katekar et al. [18] reported that the addition of 30% aluminum oxide nanoparticles to dull black paint enhanced heat transfer and thermal performance of absorber plates by a significant factor, whereas Gurbuz et al. [19] reported that nano-enhanced black paint with Fe₃O₄ and mesh tubes increased the efficiency of solar air collector by 40.45% and a payback period of 0.31-0.34 years. On the same note, Sivakumar et al. [20] demonstrated that CuO nanoparticle-coated absorber plates in a mixed-mode forced convection solar dryer enhanced collector efficiency by 4% and drying time by 6%. Performance has also been enhanced by structural and material changes to the absorber plates. Sakhaei et al., [21] reported that carbon-coated plates were the most efficient thermally (69.4%), which is 13 and 11.3% higher than the black chrome and black-painted plates, respectively. Sharma et al. [22] indicated that trapezoidal corrugated absorber plates in flat-plate solar collectors increased thermal efficiency by 12.85% and exergy efficiency by 23.31% and Kumar et al. [23] indicated that V-shaped rib roughness on absorber plates enhanced heat transfer despite higher friction factor properties. Also, Karthikeyan et al. [24] discovered that pin-fin absorber plates coated with Multi-Walled Carbon Nanotube (MWCNT) had 12% thermo-hydraulic efficiency and a 24% heat transfer enhancement. Cost-effective performance gains have also been realized by alternative absorber materials. Selikhov et al. [25] have shown that flat-plate solar collectors with polyethylene film absorbers had a maximum efficiency of 0.95 and were up to four times cheaper than aluminum absorbers. In addition, Ganesh Kumar et al. [26] emphasized that the combination of nano-coated conch shells and roughened corrugated copper absorber plates in a two-slope solar still enhanced the thermal efficiency by 35.53% and the water yield to 2193 ml/m²/day. In general, this paper point to the usefulness of nanoparticle-enhanced coating, structural changes, and alternative material to enhance the thermal efficiency, heat transfer, and economic viability of solar thermal absorber plates. The investigation of nanomaterials in solar thermal systems mainly focuses on steady-state conditions and simplified scenarios without adequate exploration of flat plate collector transient thermal responses under genuine solar and environmental fluctuations. The current investigation develops a complete transient thermal model through MATLAB that evaluates the dynamic characteristics of flat plate solar collectors using different nanoparticle materials. The model analyzes true-time solar irradiance and ambient temperature data points using Maxwell model calculations for effective thermal conductivity determination through nanoparticle selection and loading rates while implementing lumped capacitive energy modeling for time-based plate temperature and efficiency measurement. The simulation framework allows researchers to measure key performance indicators at instant efficiency rates, stagnation temperature levels and yearly energy production levels across various coating configurations thus creating a strong evaluation and material optimization environment.

II. MATHEMATICAL MODELING

The use of nanomaterials to improve thermal performance of flat plate solar collectors (FPCs) has received significant interest over the past few years. These surfaces are made of nanoparticles like graphene, CuO, and Al₂O₃ and are reported to have a tremendous effect on optical and thermal conductivity properties of the absorber plates. To measure such improvements and their effects on the performance of the system, a strict and dynamic mathematical model is necessary to capture the transient thermal behaviors at different solar and environmental conditions. This paper has constructed a MATLAB based simulation code to analyze the thermal efficiency and the energy production of flat plate collectors covered with different nanoparticle materials at varying concentrations. The code has first principles of heat transfer, with dynamic environmental inputs of solar radiation and ambient temperature, and computes key performance indicators of instantaneous collector efficiency, stagnation temperature and annual energy yield. This method offers a strong and scalable platform of comparative performance analysis of advanced coated absorbers in real-life operating environments.

II.1 KEY ASSUMPTIONS AND INPUT PARAMETERS

When formulating the thermal model of the nanoparticle-enhanced flat plate solar collector, a number of assumptions were made to reduce the complexity of the analysis without losing physical relevance. The incident of solar radiation on the collector surface was modeled as a sinusoidal curve, with the sunrise at 6:00 AM and the sunset at 6:00 PM, thus, representing the common diurnal variation in the solar irradiance. Likewise, the ambient temperature pattern was also sinusoidal with the lowest temperature at the beginning of the morning and the highest at the mid-afternoon, which closely approximates the natural environmental conditions. The absorber plate was assumed to be coated with graphene nanoparticles, whose thermal conductivity and solar absorptivity were considered to vary as functions of their concentration in the base material. In order to simulate the heat transfer behavior in the absorber plate, a lumped capacitance method was chosen. This assumes uniform temperature distribution across the plate thickness, which is valid given the small thickness of the plate and the relatively high thermal conductivity of the coated material. These assumptions collectively enabled a computationally efficient yet realistic simulation of the transient thermal behavior of the solar collector.

II.2 CODE DEVELOPMENT PROCEDURE

A simulation code was written in MATLAB to simulate the transient thermal performance of nanoparticle-enhanced flat plate solar collectors. The code is structured and modular, consisting of input definition, property enhancement, transient thermal simulation, performance analysis and result visualization. This systematic system enables the successful comparison of performance in different coating conditions.

- Input Module: Characterizes absorber geometry, coating parameters and environmental conditions (solar radiation and ambient temperature).
- Property Enhancement: Computes effective thermal conductivity, based on the Maxwell model and recalculates specific heat and density.
- Transient Module: Uses lumped capacitance model to model time-based temperature variation across the plate.
- Performance Module: Calculates instantaneous thermal efficiency, daily production and approximates yearly energy gain.
- Output and Visualization: Plots time-series data of irradiance, temperature and efficiency; compares materials and concentrations.
- Modular Design: Allows the flexibility of expansion and future upgrades or parametric studies.

II.3 CODE PERFORMANCE EVALUATION PROCEDURE

A systematic performance evaluation procedure was used to evaluate the accuracy and applicability of the developed MATLAB simulation code. This included comparing the numerical forecasts with benchmark data, sensitivity and parametric analysis and estimating long term energy production under different conditions. The steps are necessary to assure that the model is reliable to reflect the thermal behavior of nanoparticle-enhanced flat plate collectors and facilitate optimization studies.

- Result validation: Comparison of simulated temperature profiles and thermal efficiencies with published experimental data or literature values of similar nanoparticle coatings were used to verify the accuracy of the model.
- Sensitivity Analysis: The effect of nanoparticle thermal conductivity and volume fraction on thermal response of the collector was examined to determine the effect of the material.
- Annual Energy Estimation: Hourly energy gains were summed up over a daily cycle and extrapolated to give the total annual energy output of the collector system.
- Stagnation Analysis: The maximum temperature of the absorber plate (stagnation temperature) was calculated, which provided information on the highest thermal loading, by assuming zero flow conditions.
- Parametric Study: A series of simulations were performed to produce contour plots and the impact of optical (absorptance α) and thermal (emittance ϵ) property variations on the performance metrics was observed.

III. NUMERICAL METHODOLOGY

III.1 OVERVIEW OF NUMERICAL MODELING

The numerical analysis in this study was conducted using a MATLAB-based finite difference method (FDM) to simulate the transient thermal behavior of a nanoparticle-enhanced flat plate solar collector absorber. The model accounts for conduction within the absorber plate, convective and radiative heat losses from the top surface, and thermal energy absorption from incident solar radiation. The impact of adding nanoparticles to the absorber coating is captured through modified thermophysical properties. The simulation includes time-dependent ambient and solar conditions to closely mimic realistic operating scenarios.

III.2 GOVERNING EQUATION

The primary equation governing the energy dynamics in the absorber plate is based on the first law of thermodynamics, applied to a control volume given by Eq. (1):

$$mC_p \frac{dT_p}{dt} = Q_{in} - Q_{loss} \quad (1)$$

T_p is the average plate temperature, C_p is the specific heat, Q_{in} is the absorbed solar energy, and Q_{loss} includes convective and radiative heat losses from the top surface. To assess thermal performance at any instant, instantaneous thermal efficiency is defined as Eq. (2):

$$\eta(t) = \frac{Q_{useful}}{I \cdot A} = \frac{Q_{in} - Q_{loss}}{I \cdot A} \quad (2)$$

Where I is solar irradiance and A is the collector area. The effective thermal conductivity of the nanoparticle-enhanced coating is estimated using the Maxwell model as given in Eq. (3):

$$k_{eff} = k_{base} \cdot \left(\frac{k_{np} + 2k_{base} + 2\phi(k_{np} - k_{base})}{k_{np} + 2k_{base} - \phi(k_{np} - k_{base})} \right) \quad (3)$$

This accounts for the influence of nanoparticle volume fraction ϕ on thermal conductivity.

III.3 BOUNDARY CONDITIONS

In the present study, the thermal behavior of the absorber plate coated with nanoparticle-enhanced paint is simulated by applying realistic boundary conditions that represent actual operating environments of flat plate solar collectors. **Top Surface Boundary Condition** The top surface of the absorber plate is exposed directly to the solar irradiance, resulting in a heat gain, while simultaneously losing heat through convection to the ambient air and radiation to the surroundings. This is modeled using a combined heat flux boundary condition expressed as Eq. (4):

$$-k \left(\frac{\partial T}{\partial y} \right)_{top} = \alpha I(t) - h_{conv}(T_s - T_{amb}) - \varepsilon \sigma (T_s^4 - T_{amb}^4) \quad (4)$$

This boundary condition ensures the simulation captures the transient and competing effects of solar heat gain and environmental heat loss. The inclusion of both convective and radiative terms allows the model to handle a wide range of environmental conditions and surface modifications. **Bottom Surface Boundary Condition** The bottom surface of the absorber plate is assumed to be thermally insulated, representing either a well-insulated bottom or negligible heat loss through the backside. This is mathematically expressed as an adiabatic boundary condition – Eq. (5):

$$\left(\frac{\partial T}{\partial y} \right)_{bottom} = 0 \quad (5)$$

This implies no heat transfer occurs across the bottom boundary, allowing the model to focus on upward heat exchange with the working fluid or air. **Lateral Edges Boundary Conditions** The lateral sides of the absorber plate are modeled using symmetry or adiabatic conditions, depending on the physical layout and insulation characteristics of the system. For a large or center-symmetric absorber plate, symmetric conditions are suitable and simplify the problem – Eq. (6):

$$\left(\frac{\partial T}{\partial x} \right)_{left/right} = 0 \quad (6)$$

This indicates that there is no net heat flow across the lateral boundaries, which is a valid assumption when the geometry or physical design suggests negligible lateral heat loss. **Initial Condition** The entire absorber plate is assumed to be at ambient temperature at the beginning of the simulation – Eq. (7):

$$T(x, y, t = 0) = T_{amb} \quad (7)$$

This defines the starting point for the transient simulation and ensures that the heat build-up due to solar exposure is captured from the beginning of the day.

III.4 NUMERICAL SCHEME AND GRID DISCRETIZATION

The absorber plate is discretized into a 2D finite difference grid, with nodes representing small control volumes. At each node, transient heat conduction is solved using either an explicit or implicit time-stepping scheme, based on the energy conservation principle. The general form of the heat conduction equation is (Eq. 8):

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (8)$$

Where α is the thermal diffusivity. The time-marching algorithm updates nodal temperatures iteratively, and convergence is verified using the following criterion (Eq. 9):

$$\max |T^{n+1} - T^n| < \varepsilon \quad (9)$$

Where ε is a user-defined tolerance for convergence. The program exits once thermal equilibrium is reached for all nodes within the tolerance.

III.5 THERMAL PERFORMANCE METRICS

To comprehensively evaluate and compare the thermal behavior of the nanoparticle-enhanced solar absorber plates and different solar still configurations, several thermal performance metrics were used. These metrics capture instantaneous, daily, and annual system responses under varying ambient and operational conditions.

1. Useful Heat Gain

The useful heat gain (Q_{useful}) is the amount of thermal energy effectively absorbed and utilized by the system to raise the fluid (or plate) temperature. It is calculated as (Eq. 10):

$$Q_{\text{useful}} = \dot{m} C_p (T_{\text{out}} - T_{\text{in}}) \quad (10)$$

This parameter is essential for quantifying the energy that contributes to desalination or heating processes.

2. Instantaneous Thermal Efficiency

The instantaneous thermal efficiency ($\eta(t)$) defines the efficiency of the absorber plate or solar still at a particular moment, based on the ratio of useful energy gain to the incident solar energy (Eq. (11)):

$$\eta(t) = \frac{Q_{\text{useful}}(t)}{I(t) \cdot A} \quad (11)$$

This metric helps assess system performance under dynamic sunlight conditions.

3. Average Daily Efficiency

To evaluate system performance over an entire day, the time-integrated thermal efficiency is computed as (Eq. 12):

$$\eta_{\text{day}} = \frac{\int_0^{t_{\text{day}}} Q_{\text{useful}}(t) dt}{\int_0^{t_{\text{day}}} I(t) \cdot A dt} \quad (12)$$

This measure smooths out short-term fluctuations and is useful for comparing systems under realistic daily cycles.

4. Annual Energy Output

The annual thermal energy output can be estimated by extrapolating daily performance to a yearly scale, assuming typical daily operation (Eq. (13)):

$$E_{\text{annual}} = Q_{\text{daily}} \times 365 \quad (13)$$

This allows for economic analysis, including cost per liter of water and energy payback period.

5. Stagnation Temperature

Stagnation temperature is the theoretical maximum temperature the absorber can reach when no heat is extracted. It provides insight into system safety and material constraints (Eq. (14)):

$$T_{\text{stag}} = T_{\text{amb}} + \frac{I \cdot \alpha}{U_L} \quad (14)$$

A higher stagnation temperature indicates better insulation or surface absorption but may also raise material degradation concerns.

6. Empirical Collector Efficiency – Hottel–Whillier–Bliss Equation For model validation, the thermal performance is also compared using empirical efficiency correlations (Eq. (15)):

$$\eta = \eta_0 - a_1 \left(\frac{T_m - T_a}{I} \right) - a_2 \left(\frac{(T_m - T_a)^2}{I} \right) \quad (15)$$

These coefficients are commonly used in standard testing (e.g., ASHRAE, ISO) for flat plate collectors. A detailed set of governing parameters-thermal, optical, and geometrical should be specified and measured to provide accurate simulation and evaluation of the thermal performance of nanoparticle-coated flat plate solar collectors. The input parameters used in the developed transient heat transfer model were the key parameters in MATLAB as shown in Table 1. These are basic performance measures like instantaneous efficiency, useful heat gain, stagnation temperature, and annual energy output, which are calculated using energy balance equations and transient fluid temperature profiles. Also, thermal and physical characteristics of the base absorber material (copper), such as thermal conductivity, specific heat, and density are added to model real-world collector behavior. Both conventional and nanoparticle coatings are defined in optical terms of absorptance and emittance to describe radiative interactions. The dimensions and material characteristics chosen are in line with typical commercial flat plate collector designs and thereby increase the practical applicability of the model and allow comparison with experimental and literature-reported data

Table 1: Key Parameters Used in the Transient Performance Analysis of Nanoparticle-Coated Flat Plate Solar Collector.

Category	Parameter	Value(s)	Source/Notes
Performance Parameters	Instantaneous Efficiency	0–100	Calculated from energy balance
	Useful Heat Gain	Dynamic	Based on fluid temperatures and flow rate
	Stagnation Temperature	60–160 (varies by case)	Analytical expression
	Annual Energy Output	Computed for each case	Integrated from daily transient results
Collector Unit Size	Collector Area	2	Typical experimental flat plate collector
	Plate Thickness	0.003	Based on commercial copper absorber plates

Base Material Properties	Base Thermal Conductivity	385	Copper (standard absorber material)
	Specific Heat	385	Copper
	Density	8960	Copper
	Absorptance	0.9	For black paint / selective coatings
	Emittance	0.05 – 0.65	Varies with coating (selective to normal paint)
Nanoparticles Used	Thermal Conductivity Graphene	-	-
	Thermal Conductivity – CuO	33	Common nanofluid additive
	Thermal Conductivity – Al ₂ O ₃	36	Common nanofluid additive
	Volume Fraction	0.01, 0.03, 0.05	1%, 3%, 5% considered

Source: Authors, (2026).

A parametric study was performed with the aim of investigating the effect of material properties and environmental parameters on collector performance. The most important parameters were systematically changed to determine their influence on transient efficiency, absorber plate temperature, and total thermal output as summarized in Table 2. These are the values of nanoparticle thermal conductivity of CuO, Al₂O₃, and graphene, volume fraction 1-5%, and optical characteristics, solar absorptance, and thermal emittance. Time-dependent profiles of the solar irradiance and ambient temperature are also integrated in the simulation through the use of sinusoidal functions to simulate realistic diurnal operating conditions. Moreover, the effective thermal conductivity of the nanoparticle-enhanced plate is computed dynamically by the Maxwell model. The model ensures a common performance baseline by keeping all the parameters constant (plate thickness, collector area, and mass flow rate) throughout the simulations. This parameter model enables a strong insight into the effect of coating composition and environmental inputs on collector performance, thus enabling the data-driven optimization of advanced absorber coatings.

Table 2: Parametric Study – Input Parameters and Their Levels.

Parameter	Levels / Values Considered	Purpose of Variation
Nanoparticle Thermal Conductivity	33 (CuO), 36 (Al ₂ O ₃), 3000 (Graphene)	To analyze material influence on heat transfer enhancement
Nanoparticle Volume Fraction	0.01, 0.03, 0.05	To assess effect of concentration on collector performance
Solar Absorptance	0.85, 0.90, 0.95	To compare optical performance of coatings
Thermal Emittance	0.05, 0.20, 0.65	To evaluate thermal losses for various coating materials
Solar Irradiance	Transient (0–1000, sinusoidal profile)	To simulate realistic daily solar input
Ambient Temperature	Transient (15–35, sinusoidal profile)	To replicate diurnal weather conditions
Plate Thermal Conductivity (Effective)	Computed via Maxwell Model	To dynamically update heat transfer properties
Plate Thickness	0.003	Fixed – standard plate design
Mass Flow Rate	0.02	To maintain consistent comparison across test cases
Collector Area	2	Fixed size for baseline comparison

Source: Authors, (2026).

III.6 SIMULATION SETUP AND COATING CONFIGURATIONS

This paper analyses thermal performance of a flat plate solar collector under different nanoparticle-enhanced absorber coating under controlled simulation conditions using a MATLAB-based transient thermal model. The main aim is to examine how various nanoparticle coating and mass flow rates affect the outlet temperature of the working fluid and consequently the thermal efficiency of the collector. The simulation model is based on the basic principles of energy conservation, and the equation of energy balance is considered to take into consideration useful heat gain, time-varying solar irradiance, ambient temperature, and heat losses due to convection and radiation. In order to consider the thermal enhancement of nanoparticles, the effective thermal conductivity of the coating layer was calculated through classical Maxwell model with the adjustment of the volume fraction and intrinsic thermal conductivity of the dispersed nanoparticles. Four absorber surface coatings were modeled: conventional black paint, copper oxide (CuO), aluminium oxide (Al₂O₃), and graphene. Each coating was evaluated at a fixed nanoparticle concentration to maintain consistency across cases and to isolate the effect of material thermal properties. The simulations were conducted for three different flow rates i.e. 0.01 kg/s, 0.02 kg/s, and 0.03 kg/s to examine the impact of mass flow rate on the system's thermal response and outlet temperature profile. This setup allowed a fine comparison of thermal performance in terms of coating types and operating conditions and provided information on the interaction between material selection and fluid dynamics to influence solar thermal collector efficiency

IV. NUMERICAL ALGORITHM

A simulation framework of a customized MATLAB was used to conduct the thermal analysis of nanoparticle-enhanced absorber plates. The transient two-dimensional heat conduction equation in the absorber plate domain was solved by the finite difference method (FDM). The general computational procedure can be summarized in the flowchart shown in Figure 1. The simulation starts with the initialisation and input of key parameters such as the geometry of the plate (length, width, and thickness), material characteristics of the base material and nanoparticles (thermal conductivity, density, specific heat), nanoparticle volume fraction (ϕ), solar radiation intensity (G), ambient temperature (T_{amb}), convective heat transfer coefficient, and plate surface emissivity. Stefan-Boltzmann constant is used to include radiation losses. Boundary conditions are then applied. The top surface of the absorber plate is subjected to combined solar radiation and convective–radiative heat losses, while the bottom surface is thermally insulated. The edges of the plate are treated as either adiabatic or symmetric, depending on symmetry considerations. Next, effective thermophysical properties of the nanocomposite plate are calculated.

These are the effective thermal conductivity (k_{eff}), which is calculated by a modified Maxwell model that considers the coupling between base material and nanoparticles, and the effective density (ρ_{eff}) and specific heat (Cp_{eff}), calculated by volume-weighted averages. This is because the computational domain is discretized with a finite difference grid, which allows calculation of the temperature at each node on discrete time steps. A time-marching loop is then initiated to solve the transient heat conduction problem using either explicit or implicit schemes. At each time increment, nodal temperatures are updated and checked for convergence. The iterative loop continues until the maximum temperature difference between two successive time steps satisfies the convergence criterion,

$$\max|T^{n+1} - T^n| < \varepsilon \quad (16)$$

The outputs of the program on convergence are the temperature distribution of the absorber plate with time, spatial temperature profiles, heat flux and thermal efficiency. Thermal efficiency is determined as the ratio of useful heat gain to the total incident solar energy, which is a complete measure of thermal performance of the plate.

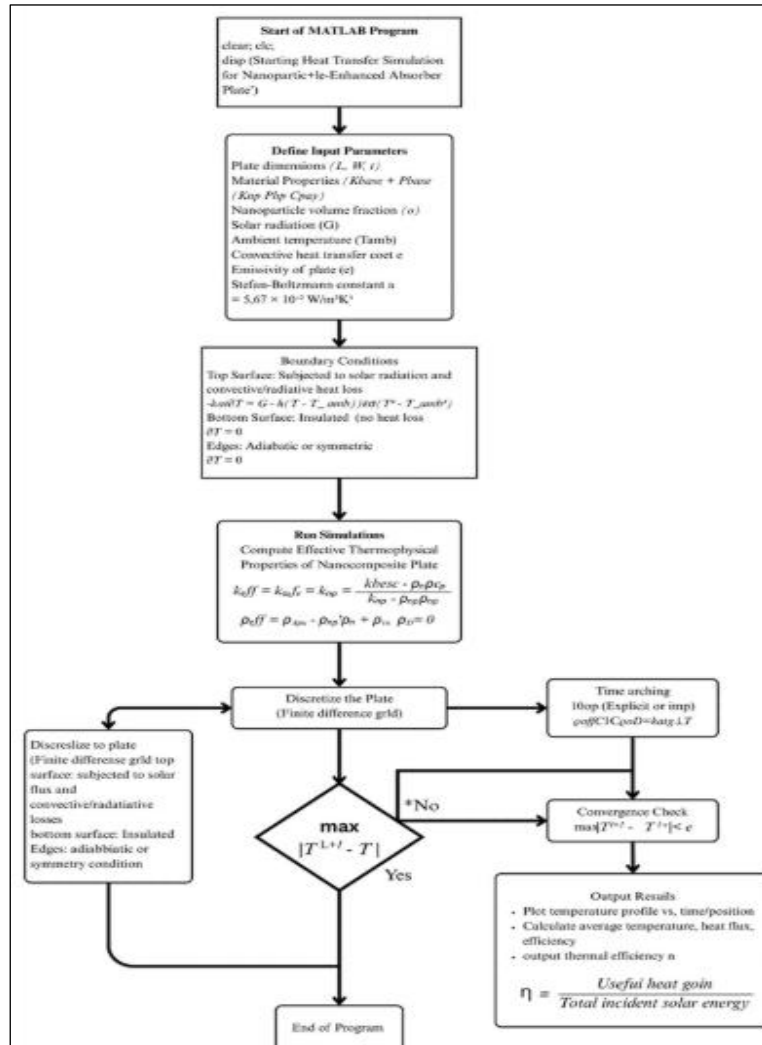


Figure 1: Flow algorithm for the MATLAB programming.
Source: Authors, (2026).

V. RESULTS AND DISCUSSIONS

V.1 VARIATION OF SOLAR RADIATION AND AMBIENT TEMPERATURE DURING TEST HOURS

Figure 2 and Figure 3 represent the variation of the solar radiation and ambient temperature of the day at the time of experiment between 9:00 AM to 2:30 PM. The solar radiation was of a normal bell-shaped pattern with the lowest value of 500 W/m² at the start of the day at 9:00 AM and the highest value of about 1000 W/m² at 10:40 AM to 11:10 AM. Subsequently, it started to decrease gradually, to about 670 W/m² at 2.30 PM. This symmetrical pattern is consistent with the natural cycle of solar altitude and it proves the good conditions of radiation to do thermal testing in the middle of the day. Simultaneously, ambient temperature also increased with time with an initial value of 30°C and reaching a peak of 40°C at noon (12:00 PM). After noon, there was a small decrease as a result of the lowering solar elevation and a lower irradiance. The ambient temperature pattern follows the solar radiation peak slightly, which means the thermal inertia of the environment. These realistic variations are needed to model transient boundary conditions in a numerical model and to predict the thermal behavior of solar collector systems. These environmental inputs were dynamic forcing functions to the heat transfer simulations and allowed accurate determination of absorber plate temperatures, thermal losses and efficiency measures in further analysis.

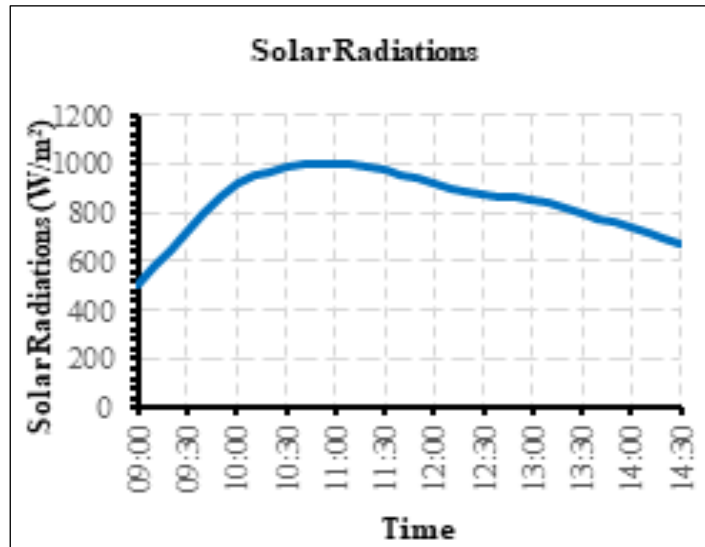


Figure 2: Variation of solar radiations during the test.
Source: Authors, (2026).

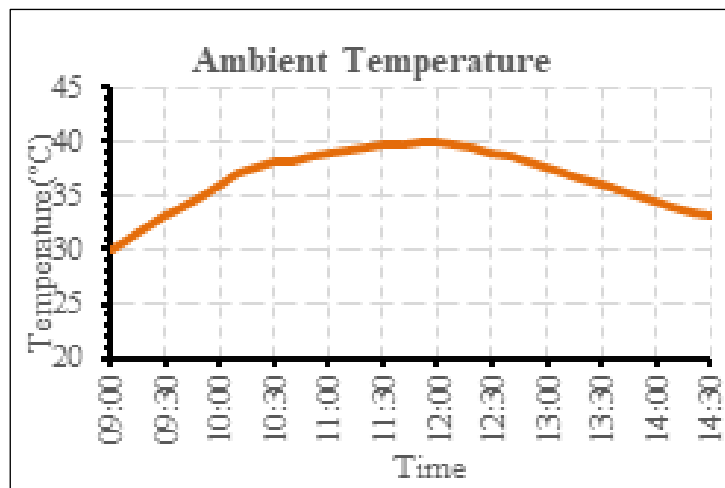


Figure 3: Variation of ambient temperature during the test.
Source: Authors, (2026).

V.2 VARIATION OF OUTLET FLUID TEMPERATURE WITH TIME

Figure 4(a)-4(d) show the change in the temperature of the outlet of the working fluid with time in the case of absorber plates painted with black, CuO, Al₂O₃, and graphene at mass flow rates of 0.01 kg/s, 0.02 kg/s, and 0.03 kg/s. Based on the graphs, it is clear that at every flow rate, graphene-coated absorber plates always record the highest outlet temperatures, then CuO, Al₂O₃, and black paint in that order of thermal performance. The graphene-coated collector achieves the highest outlet temperature of 59.29°C at the lowest flow rate of 0.01 kg/s, which is about 4.54, 5.86 and 9.4 higher than CuO (56.69°C), Al₂O₃ (55.98°C) and black paint (54.18°C). The improvement in performance of graphene coatings is mostly because of its high thermal conductivity and optical absorptivity. The large thermal diffusivity of graphene allows quick heat transfer over the absorber surface, minimizing hotspots locally and ensuring a uniform temperature gradient. CuO and Al₂O₃ also provide better thermal response than traditional black paint because of their nanostructured structure that increases the effective surface area to transfer heat and the convective heat transfer coefficient at the absorber-fluid interface. The outlet temperature decreases significantly as the flow rate rises between 0.01 kg/s and 0.03 kg/s in all the types of coatings. This is a direct effect of the lower thermal residence time of the working fluid within the collector tube, which restricts the quantity of heat absorbed. To illustrate, the temperature of the outlet of graphene decreases to 54.92°C at 0.02 kg/s and to 51.62°C at 0.03 kg/s - a relative decrease of 6.3 and 12.9%, respectively, of its maximum value at 0.01 kg/s. On the same note, the black paint coating drops are reduced by almost 9.2% and 14.7% respectively as the flow rate increments. This validates the assertion that low flow rates are better suited to higher outlet temperatures because of extended heat exchange whereas higher flow rates are more advantageous in regards to total thermal energy removal because of greater fluid volume. Furthermore, the average temperature of the outlet measured throughout the whole time of the experiment also proves the better thermal performance of graphene. The average temperature of graphene at a rate of 0.01 kg/s is 55.17°C, whereas the average temperature of CuO, Al₂O₃, and black paint are 52.89°C and 50.47°C respectively. This pattern is always preserved at increased flow rates, but the temperature differences become a little smaller as a result of greater convective dominance. In general, the findings indicate clearly the high thermal performance of graphene as an absorber coating material, particularly when flow rate conditions are low and the properties of the absorber surface dominate the heat transfer processes.

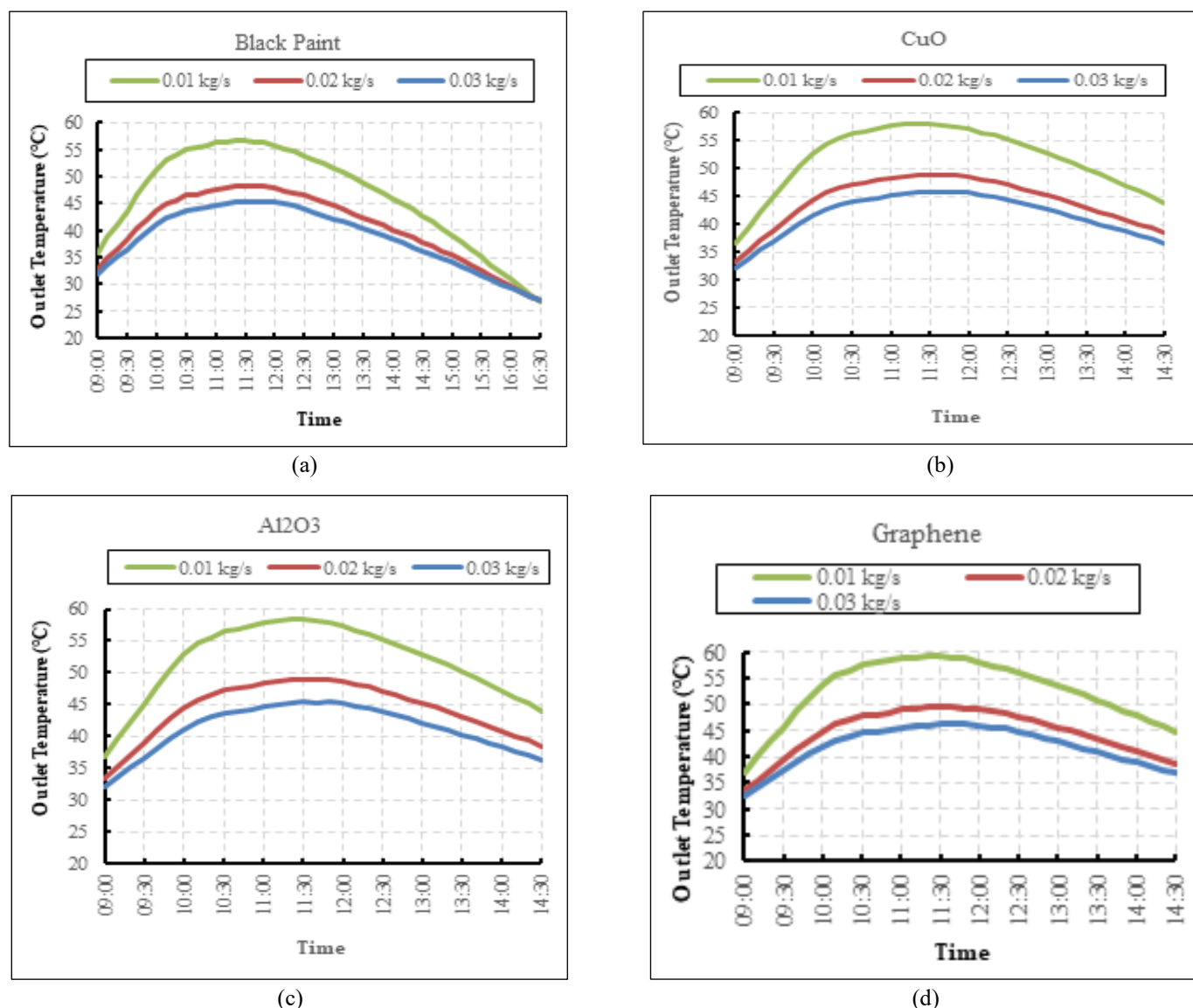


Figure 4: Variation of fluid outlet temperature at various fluid flow rates with (a) Black paint coated, (b) CuO coated, (c) Al₂O₃ coated and (d) Graphene coated absorber plate.

Source: Authors, (2026).

V.3 EFFECT OF NANOPARTICLE MATERIAL ON HEAT GAIN

Figure 5 shows the change in useful heat gain of flat plate solar collectors coated with black paint, CuO, Al₂O₃ and graphene at a constant mass flow rate of 0.01 kg/s. The results indicate a strong improvement in thermal performance when nanomaterial-based coating, especially graphene is used instead of the standard black paint. The useful heat gain of all the coatings increased steadily as the solar radiation increased during the morning, reaching its highest point in the middle of the day and then decreasing in the afternoon as the sun faded. This day/night cycle is common to solar thermal systems, but the degree of heat gain differs greatly across the various coatings, suggesting the importance of improved thermal and optical characteristics. The graphene-coated absorber recorded the highest heat gain during the entire test period with the peak of 834W recorded at 11:00 AM. Comparatively, the highest values obtained on Al₂O₃, CuO and black paint were 794W, 784W and 724W respectively. This is equivalent to a maximum increase of about 15.2% of graphene against black paint, 5.0% of graphene against CuO and 5.0% of graphene against Al₂O₃. These high-performance properties of graphene can be explained by its high thermal conductivity that increases the heat transfer rate between the absorber plate and the working fluid. Also, graphene has high solar absorptance and low emittance, which enhance solar energy capture and retention. Its two-dimensional lattice structure is unique and enables fast phonon transport, which lowers interfacial thermal resistance and enables energy conversion to be more efficient. There were also significant improvements with CuO and Al₂O₃ coatings, Al₂O₃ always slightly better than CuO. These metal oxide nanoparticles have a moderate thermal conductivity and higher surface absorptivity than black paint, which explains the fact that these nanoparticles perform better. Graphene continued to have a visible advantage in useful heat gain over the entire time range, suggesting that it does not just enhance peak performance, but also allows it to remain in higher energy conversion efficiency even in sub-optimal solar conditions. These findings support the importance of the coating material choice in maximizing the collector efficiency, especially in low flow rate conditions where thermal inertia is stronger.

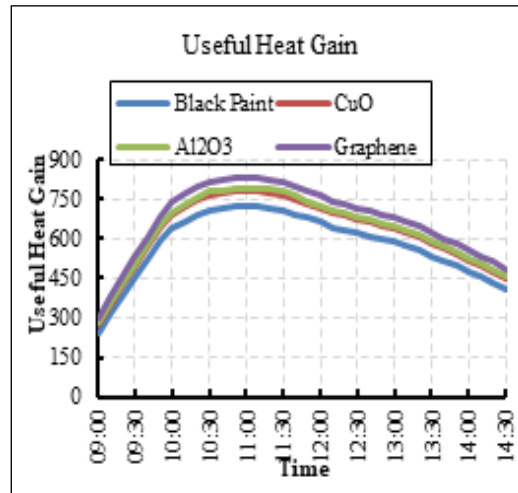


Figure 5: Comparison of useful heat with different absorber plate coatings.
Source: Authors, (2026).

V.4 COMPARISON OF USEFUL HEAT WITH DIFFERENT ABSORBER PLATE COATINGS

Figure 6 shows the variation of instantaneous thermal efficiency of the various absorber plate coatings at constant flow rate of 0.01 kg/s. The coatings that have been studied are conventional black paint and nanomaterial-based coatings which are CuO, Al₂O₃, and graphene. The thermal efficiency is evidently correlated with the nature of coating as a result of variations in optical and thermal characteristics. Graphene was the most efficient of all the coatings and it was also the most efficient during the day with a peak of 0.8353 at around 11:20 AM. This high performance is explained by the outstanding thermal conductivity and high solar absorptivity of graphene that increase the rate of heat transfer between the absorber surface and the working fluid. CuO and Al₂O₃ were also more efficient than the black paint coating with maximum values of 0.7853 and 0.7953 respectively, which were obtained at the same period of high radiation. These nanomaterials of metal oxide enhance the surface area and thermal diffusivity, which results into the lessening of thermal resistance between the coating and the fluid. Comparatively, the traditional black paint coating had the lowest efficiency of 0.7253 and hence was the least efficient of the four. CuO, Al₂O₃ and graphene had a percentage improvement in peak efficiency of approximately 8.27, 9.64 and 15.17 respectively as compared to black paint. The overall pattern of Figure 6 is that efficiency gradually rises between 9:00 AM and about 11:30 AM and then gradually decreases because of the decreasing solar irradiance and a decrease in the temperature gradient between the plate and the fluid. Nevertheless, less efficient coatings (particularly graphene) remained more efficient in the later hours because they could extract and transfer heat more efficiently at lower irradiance. This shows that nanomaterial-based coating does not only improve peak performance but also provides sustained thermal performance over a broader operating range.

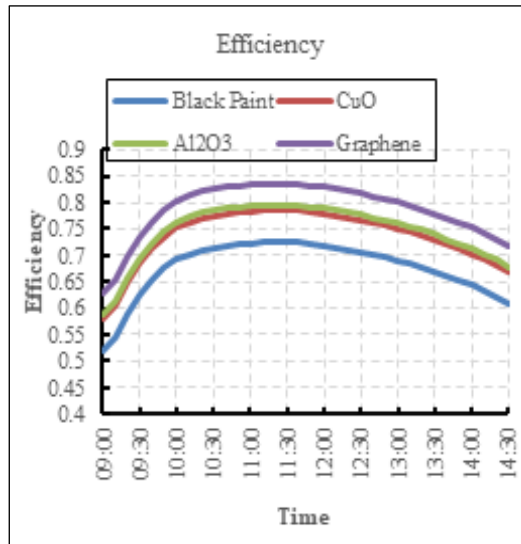


Figure 6: Variation of collector efficiency for different absorber plate coatings at a flow rate of 0.01 kg/s.
Source: Authors, (2026).

VI. CONCLUSIONS

This work provides detailed numerical research on the improvement of thermal performance of flat plate solar collectors (FPCs) with nanoparticle-based absorber coating, such as CuO, Al₂O₃, and graphene. A transient MATLAB-based model was developed and validated to assess the effect of nanoparticle coatings on outlet fluid temperature, useful heat gain, and thermal efficiency under varying operating conditions. Key conclusions drawn from the study are:

- The performance of nanoparticle-coated absorber plates was far superior to that of conventional black paint in all the measures of thermal performance.
- Collectors covered with graphene had the highest thermal efficiency with a maximum of over 0.83, about 15% higher than black paint.
- Al₂O₃ and CuO coating also offered significant gains in useful heat gain of about 8-10% and 6-8% respectively over black paint.
- The increase in performance has been credited to the fact that the nanomaterials have better optical absorption and thermal conductivity that minimizes thermal losses and enhances the heat transfer.
- The graphene-coated collector retained a higher performance even at lower irradiance periods, which showed an increased thermal inertia and heat retention.

The next step in research should be experimental validation and stability analysis of nanomaterial coating in the real outdoor conditions in the long-term.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Methodology: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Investigation: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Discussion of results: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Writing – Original Draft: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Writing – Review and Editing: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Resources: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Supervision: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

Approval of the final text: Juber Khatik, Nilesh Salunke, Mujahid Husain, Yogeshkumar Pathak, Kailas Deore, Pradeep Solanki and Pravin Shirule.

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