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Research Article

Parameters optimization of solar-based incubation room for fermented dairy products

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Abstract

Solar-based incubation rooms meant for producing fermented dairy foods demonstrated consistent performance with economic benefits and reduces its reliance on non-renewable energy sources. This research aims to optimize the operational parameters of a solar-based incubation room having capacity of 1200 L of milk meant specifically for producing fermented dairy products. Response Surface Methodology (RSM) systematically investigates factors influencing energy consumption. Thermal energy was free of cost while the electrical energy meant for the circulation of hot water from the storage tank to the incubation room and for air circulation within the incubation room. Experimental trials revealed significant effects of fan speed, hot water flow rate (based on frequency of hot water pump), relative humidity (RH) of air in incubation room, and hot water temperature on the total electrical energy consumption required in solar-based incubation room. The optimized parameters recommended based on the current study involved using fan speed of 3, 42.5 Hz pump frequency, 60% RH, and keeping hot water temperature at 68°C, resulting in a desirability of 1.0 and consuming 0.885 kW h electrical energy per batch of 4 hours of operation. Implementation of such recommended practices will culminate in improved energy efficiency at the dairy factory and aid in achieving sustainability in dairy production with payback period of 3 years and 8 months.

Keywords: Energy efficiency, Fermented dairy products, Incubation room, Optimization, Solar energy

Highlights

- Electrical heaters are used in incubation room for fermented dairy products to maintain the temperature of room as well as products for better growth of starter culture.
- The solar water heater has been used for maintaining the temperature in the room using hot water circulation pump.
- The present study deals with the optimization of speed of hot water circulation pump, speed of blower of heat exchanger, relative humidity of air and temperature of hot water.
- We can have payback period of 3 years and 8 months of solar-based incubation room by saving energy used in traditional electrical heaters.

INTRODUCTION

The escalating demand for fermented dairy products, such as *dahi*, *chhas*, probiotics, and other functional fermented dairy foods reflects growing awareness of their associated health benefits in human race. In the manufacturing process of these fermented products, maintaining specific incubation temperatures, typically ranging between 37 and 45°C, is imperative for the optimal growth of starter cultures that were inoculated in the milk. Traditionally, electrical air heating systems have been employed in dairy plants to regulate the temperature within the incubation room in a dairy plant. However, the requirement for substantial power consumption to operate such systems, influenced by ambient conditions, electricity costs, and incubation room capacity, poses environmental and economic concerns.

Addressing the burgeoning energy demand and the detrimental impact on environment can be attributed to the use of conventional energy sources. Under such circumstances, there is a marked global shift towards harnessing renewable energy alternatives in the modern dairy plants. Solar energy emerges as a promising solution, being the most abundant renewable energy resource, with an immense energy output estimated at 3.8×10^{23} kW. Notably, approximately 1.8×10^{14} kW of solar energy is intercepted by the Earth, primarily manifesting in the form of heat and light (Panwar et al., 2011; Duffie et al., 2013). Leveraging available technologies, solar radiation can be efficiently converted into heat energy, enabling solar energy systems adaptable to various applications in dairy plants (Masera et al., 2023).

In this context, the utilization of solar energy for

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incubation rooms meant for producing fermented dairy products offers a compelling alternative to the orthodox electrical air heaters (Agrawal et al., 2014). Solar thermal systems can effectively generate hot water during daylight hours, which can then be utilized to maintain the requisite temperatures required in the incubation rooms. Promisingly, solar-based incubation rooms demonstrate consistent performance across seasons, exhibiting solar fractions ranging from 0.81 to 1.00 (Chauhan & Bhadania, 2019). Notably, supplementary thermal energy is deemed unnecessary for about four months of the year, with the remaining months requiring only modest supplemental thermal inputs, accounting for 8-9% of the total thermal energy requirements (Chauhan & Bhadania, 2019).

In order to avail of these promising outcomes for energy, there arises a need to optimize the operational parameters of solar-based incubation rooms to maximize energy efficiency and minimize the dairy plants' reliance on non-renewable energy sources (Sinha et al., 2025). This research endeavors to systematically investigate and optimize the key operational parameters in enhancing the performance and sustainability of solar-based Incubation systems for producing fermented dairy products, involving fan speed, hot water circulation pump frequency (flow rate), Relative Humidity (RH) of air and temperature of hot water. Through rigorous experimentation and statistical analysis, this study seeks to elucidate the interplay between these parameters and determine the total electrical power consumption to arrive at the power economy. The recommendations from this study will pave the way for effective and environmentally friendly dairy production practices.

MATERIALS AND METHODS

The aim of this research was to optimize the operational parameters of a solar-based incubation room. The volume of incubation roomwas 10.0 m^3 (V= L x B x H, i.e. $2 \times 2 \times 2.5$) for the production of fermented dairy products. This entails utilizing solar energy to maintain the requisite temperature during the incubation process, thereby conserving electrical or thermal energy, typically otherwise derived from fossil fuels. In order to achieve this, various operational parameters such as fan speed, hot water circulation pump frequency (flow rate), Relative Humidity (RH) of air and temperature of hot water were investigated to study their influence on the total electrical energy consumption used by the system.

Experimental setup: The experimental setup for the solar-based incubation room for dairy plant comprised of evacuated tube type solar collectors (Fig. 1) having 10 m^2 aperture area with heat pipe for capturing solar energy, a thermal energy (hot water) storage tank (Fig. 2), a water circulation pump (Fig. 3 and 4), a coiledheat exchanger incorporating fins (Fig. 5), and associated pipelines for efficient thermal energy transfer (Fig. 3).The Evacuated Tube type Collector with Heat Pipe (ETC-HP) was used to convert the energy of solar radiation in the form of hot water. Thermal energy in the form of hot water was stored in an insulated storage tank with 10000 L capacity. The hot water from storage tank was circulated through the induced draft Finned Coiled Heat Exchanger (FCHE) installed in the incubation room (Fig. 6) to maintain its temperature. Thermostat was installed in the system in order to start or stop the hot water pump and open or

Fig. 1. Solar hot water heating system with evacuated tube collector with heat pipe

Fig. 2. Hot water storage tank

Fig. 3. Pipeline for hot water circulation from tank to the incubation room

Fig. 4. Pump for hot water circulation

Fig. 5. Hot water fed to air heat exchanger

Fig. 6 (6a, 6b & 6c). Solar-based incubation room

close the solenoid valves of water supply, as per need, to the FCHE. The hot water circulation in ETC-HP was operated using solar Photo Voltaic (PV) panel during daytime (Sain & Sharma, 2024). Our intention was to minimize the electrical energy required by the pump for circulation of hot water from storage tank to FCHE in incubation room.

Selected operating parameters with boundary conditions

The optimization process focused on four pivotal operating parameters, namely Hot water temperature range 50 to 70°C, chosen based on thermal efficiency considerations, Relative Humidity range 30.0 to 70.0%, normal room condition, Fan/Blower speed levels 1 to 5, facilitating precise control over air circulation and Hot water flow rate range 0 to 50.0 Hz, aligning with the operational capacity of the circulation pump. Temperature of hot water was maintained using thermostat, % RH was maintained using water spray or dehumidification by cooling coil.

Experimental procedure

Sample preparation: Water, representative of the fermentation medium, was packaged in 500 mL pouches and distributed across 100 crates (471 mm x 378 mm x 168 mm), each containing 24 pouches. As the specific heat of water (4.186 kJ/kg K) is higher than that of milk (3.9 kJ/kg K), the overall saving in milk would be higher than whatever we get in water.

A total of 1200 L of water (equivalent to 2400 pouches) was placed in the experimental incubation room. The heat exchanger fan ran continuously throughout the incubation period to ensure uniform air distribution and efficient heat transfer. Two energy meters were deployed to quantify the energy requirement by the fan and hot water circulation pump per batch of 4 hours. Total energy consumption data was meticulously recorded for each experimental run.

Energy saving potential of the solar based incubation room: A traditional electrical room heater was installed in the solar based incubation room and electrical energy consumed per batch by the electrical heater was determined using energy meter. The energy saving potential was determined by comparing the electrical energy consumed per batch using electrical heater to maintain the incubation temperature in the incubation room without using solar energy with the total energy consumed per batch by the solar based incubation room. The savings of amount of energy per year were calculated.

Statistical analysis: Utilizing Design Expert 11.0.3.0 software, the collected data underwent rigorous statistical analysis to elucidate the interplay between the selected factors and the total electrical energy consumption. The software facilitated recommendation of optimized combinations of operating parameters, ensuring maximum energy efficiency within the incubation system (Managamuri et al., 2016).

RESULTS

Optimizing the operating parameters for the solar-based incubation room: The solar-based incubation room allows for the adjustment of operating parameters such as hot water temperature and its flow rate, RH of air and air velocity. The thermostat maintained a

Table 1. Energy consumption during operation of solar based-incubation room

Run	Fan speed (Level)	Relative Humidity (% RH)	Frequency of pump (Hz)	Temperature of hot water (°C)	Energy consumption by the system components/batch (kWh)		
					Pump	Fan	Total
1	3	50	45.0	60	0.900	0.246	1.146
2	3	50	45.0	60	0.827	0.246	1.073
3	4	60	47.5	65	0.815	0.295	1.110
4	3	50	45.0	60	0.825	0.246	1.071
5	2	60	47.5	65	1.041	0.226	1.267
6	3	50	45.0	50	1.581	0.246	1.827
7	3	70	45.0	60	0.845	0.246	1.092
8	2	40	47.5	65	1.101	0.226	1.327
9	1	50	45.0	60	1.379	0.200	1.579
10	4	40	42.5	55	1.172	0.295	1.467
11	3	50	50.0	60	1.080	0.246	1.326
12	3	30	45.0	60	0.793	0.246	1.039
13	2	60	47.5	55	1.532	0.226	1.758
14	4	40	42.5	65	0.656	0.295	0.951
15	4	60	42.5	55	1.144	0.295	1.440
16	4	60	47.5	55	1.400	0.295	1.696
17	2	40	42.5	55	1.132	0.226	1.357
18	5	50	45.0	60	1.061	0.337	1.397
19	3	50	40.0	60	0.681	0.246	0.927
20	3	50	45.0	70	0.660	0.246	0.906
21	2	40	42.5	65	0.845	0.226	1.071
22	3	50	45.0	60	0.807	0.246	1.053
23	2	60	42.5	55	1.112	0.226	1.338
24	2	40	45.0	55	1.495	0.226	1.441
25	4	40	47.5	55	1.412	0.295	1.707
26	4	40	47.5	65	0.826	0.295	1.121
27	2	60	42.5	65	0.865	0.226	1.090
28	3	50	45.0	60	0.830	0.246	1.076
29	4	60	42.5	65	0.691	0.295	0.987
30	3	50	45.0	60	0.835	0.246	1.082

temperature of 41±2°C in the incubation room. Optimization was conducted at full capacity (100 crates, 1200 kg water).

A variable frequency drive (VFD) regulated the hot water flow rate, affecting the mass flow rate through the water to the air heat exchanger (i.e. FCHE).

Energy consumption analysis: Experimental trials were conducted to arrive at the optimal operating conditions for the system, considering various combinations of parameters. The energy consumption by the fan and pump was measured. Table 1 shows the energy consumed by the system during operation of the incubation room. The electrical energy requirement by the hot water pump ranged from 0.656 kWh to 1.581 kWh per batch; the energy consumption by the fan varied from 0.200 to 0.337 kWh per batch. These led to the total electrical energy consumption ranging from 0.906 kWh to 1.827 kWh per batch, with a mean of 1.257±0.26 kWh.

The quadratic model for energy analysis, derived through ANOVA, is depicted in Table 2. With a Model F-value of 42.63, the model is deemed significant, suggesting a mere 0.01% likelihood of such a large F-value occurring due to noise. p-values below 0.0500 affirm the significance of model terms, while values exceeding 0.1000 indicate non-significant. A Lack of Fit F-value of 4.24 suggested 6.23% chance of occurrence due to noise. Fit statistics validated the model, with a coefficient of determination (R^2) of 0.9755. Additionally, the Adequate Precision Value (APV) of 22.62 surpassed the minimum desirable value of 4.00, endorsing the model's prediction ability. The analysis revealed that the Fan speed (A), Frequency of hot water pump (C), and Temperature of hot water (D) exerted significant ($p<0.01$) negative effects on the total electrical energy consumption. Conversely, RH of air (B) exhibited a non-significant linear effect. Interactions between Fan speed and Temperature of hot water (AD) displayed a significant negative impact on energy consumption. However, interaction betweenfan speed and RH of air (AB); interaction betweenfan speed and frequency of hot water pump motor (AC); interaction between RH of air with frequency of hot water pump motor (BC) and temperature of hot water (BD); and interaction between Frequency of hot water pump with temperature of hot water (CD) were found to be non-significants. The squared terms (A^2, C^2, D^2) revealed significant ($p<0.05$) negative effects on the energy consumption at higher levels of Fan speed, Frequency of hot water pump, and Temperature of hot water. Fig. 7 to 12 shows interaction effects of hot water temperature, % Relative humidity of air, frequency of hot water pump and speed of fan for air circulation on total energy consumption by the fan and hot water pump.

Table 2. ANOVA for quadratic model for total energy consumption as response

Source	Sum of Squares	Df#	Mean Sum of Squares	F-value	p-value	Remark
Model	1.95	14	0.14	42.63	< 0.0001	significant
A-Fan Speed	$2.16*10^{-2}$	1	0.02	6.62	0.0212	
B-RH	$0.10*10^{-2}$	1	$0.10*10^{-2}$	0.32	0.5822	
C-Frequency	0.29	1	0.29	88.92	< 0.0001	
D-Temperature	1.16	1	1.16	355.27	< 0.0001	
AB	$0.04*10^{-2}$	1	$0.04*10^{-2}$	0.12	0.7387	
AC	$0.75*10^{-2}$	1	$0.75*10^{-2}$	2.31	0.1491	
AD	0.04	1	0.04	12.30	0.0032	
BC	$1.86*10^{-6}$	1	$1.86*10^{-6}$	$0.06*10^{-2}$	0.9812	
BD	$0.04*10^{-2}$	1	$0.04*10^{-2}$	0.13	0.7197	
CD	$1.36*10^{-2}$	1	$1.36*10^{-2}$	4.17	0.0592	
A^2	0.35	1	0.35	107.20	< 0.0001	
B^2	$0.15*10^{-2}$	1	$0.15*10^{-2}$	0.47	0.5052	
C^2	$1.53*10^{-2}$	1	$1.53*10^{-2}$	4.68	0.0471	
D^2	0.19	1	0.19	57.34	< 0.0001	
Residual	0.05	15	$0.33*10^{-2}$			
Lack of Fit	0.04	10	$0.44*10^{-2}$	4.24	0.0623	Non-significant
Pure Error	$0.52*10^{-2}$	5	$0.10*10^{-2}$			
Cor Total*	1.99	29				

*Cor Total - Corrected Total Sum of Squares, Df#- degrees of freedom

A multiple regression equation was derived to predict the total electrical energy consumed by the system taking into consideration the various factors (A, B, C and D) representing fan speed, RH of air, frequency of hot water pump (Hz), and hot water temperature (°C). The equation is as follows:

Total Energy consumption by the system = $12.40418 + 0.337935\times A + 0.000363\times B - 0.119012\times C - 0.294399\times D - 0.000491\times AB - 0.009205\times AC - 0.010131\times AD + 0.000014\times BC - 0.000106\times BD - 0.002471\times CD + 0.113082\times A^2 + 0.000075\times B^2 + 0.003777\times C^2 + 0.003308\times D^2$

Interaction effects among operating parameters on the total electrical energy consumption based on the above model were studied, varying the four parameters within the experimental range.

When fan speed (A) and hot water temperature (D) were at the center point, increasing the fan speed initially raised the energy requirement, which decreased later on, beyond a certain limit. Opposing the above finding, increasing the hot water pump frequency (C) under constant RH and temperature elevated the energy requirement. An increase in the hot water temperature (D) reduced the energy consumption at constant fan speed and pump frequency.

Optimization of operating parameters aimed to minimize the total electrical energy requirement involved arriving at the best combinations of fan speed, RH of air, hot water pump frequency and the hot water

Table 3. Criteria/response chosen for optimizing the operating parameters for the solar based incubation room

Sr. no.	Parameters	Units	Goal	Lower Limit	Upper Limit	Level of Importance
1	A: Fan Speed	Level	In range	2	4	3
2	B: Relative Humidity	%	Maximum	40	60	3
3	C: Frequency of Pump	Hz	Minimum	42.5	47.5	3
4	D: Temperature	°C	In range	55	70	3
5	Total Energy Consumption per Batch	kWh	Minimum	0.906	1.827	3

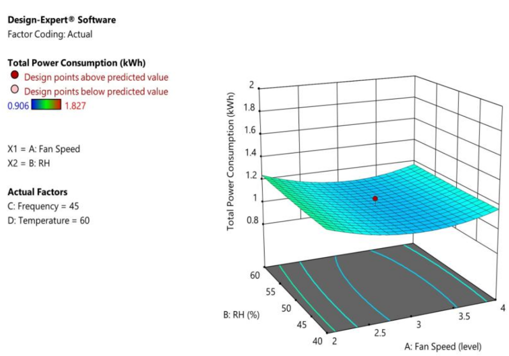

Fig. 7. Effect of relative humidity and fan speed on total power consumption of the system

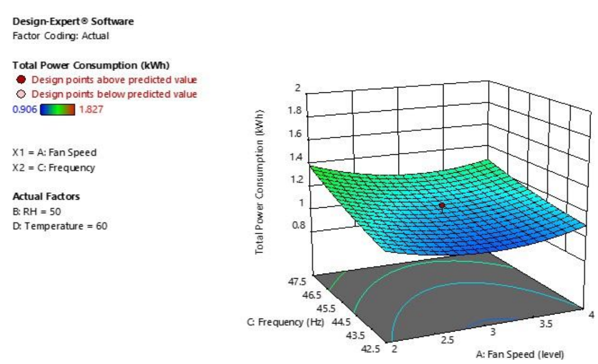

Fig. 8. Effect of frequency of hot water pump and fan speed on total power consumption of the system

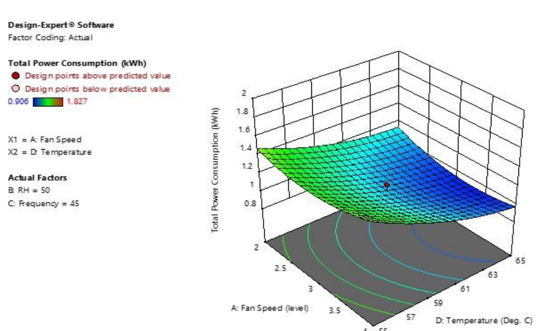

Fig. 9. Effect of temperature of hot water and fan speed on total power consumption of the system

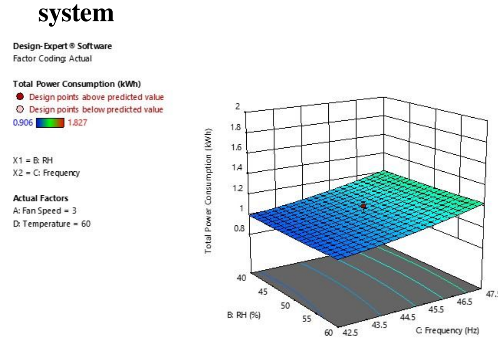

Fig. 10. Effect of relative humidity of air and frequency of pump on total power consumption of the system

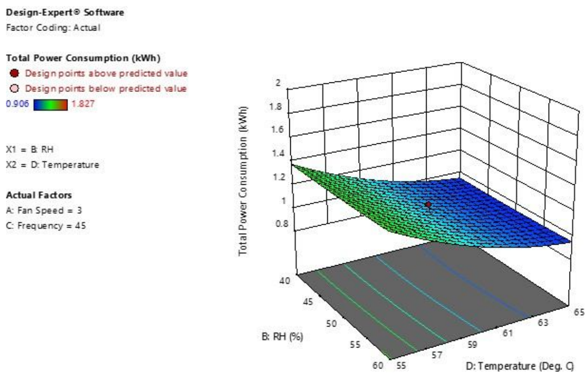

Fig. 11. Effect of relative humidity of air and temperature of hot water on total power consumption of the system

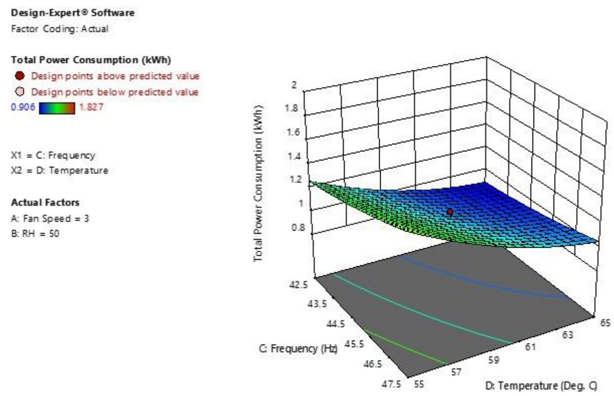

Fig. 12. Effect of frequency of pump and temperature of hot water on total power consumption of the system

Table 4. Suggested solution from RSM analysis for operating parameters meant for solar-based incubation room

Solution number	Factors				Desirability	Response: Total energy consumption per batch (kWh)
	A: Fan speed	B: Relative Humidity (%)	C: Frequency of pump (Hz)	D: Temperature of water (^oC)		
1	3	60.0	42.5	68	1.0	0.885

Table 5. Comparison of predicted v/s actual values of responses used for the optimization of operating parameter for solar based incubation room

Response	Predicted value	Actual value	Calculated t-value	p-value	Level of significance
Total Electrical energy consumption per batch (kWh)	0.885	0.885±0.003	0.3536	0.7358	Non-Significant

temperature (Table 3). Based on the parameters and their constraints, analysis by RSM identified the most suitable solution. The optimal solution suggested by RSM analysis for the incubation room's operating parameters is presented in Table 4, achieving a desirability of 1.0 with total energy consumption of 0.885 kWh per batch (4 hours). Subsequently, seven trials were conducted using the optimized operating parameters, and the total energy consumption was determined. Table 5 illustrated both the predicted and actual values of total energy consumed by the system. The mean value of total energy consumption was 0.885 kWh, with a calculated t-value of 0.3536. The effect was deemed non-significant, with a P-value of 0.7358.

For estimating energy saving potential, electrical air heater was installed in the incubation room and it was operated to maintain the same level of temperature as it was maintained by solar thermal system. Total seven trials were taken using electrical heater in the incubation room. The average electrical energy consumed by the traditional electrical heater per batch was found to be 5.556±0.016 kWh (n=7). It was found that 4.671 kWh energy was saved per batch by using solar thermal system instead of electrical air heaters. Considering 300 days of operation of the incubation room, 6 batches of product per day, Rs. 6.50 cost of electricity per kWh; it was estimated that about Rs. 54650.00 can be saved by using solar based incubation room in place of traditional electrical heater. If we consider Rs. 2 lakh initial investment cost for the solar based incubation room, 3.66 years (3 years and 8 months) will be the payback period of the system. At the end of optimization, we had installed a PV panel with suitable capacity to operate the motors of hot water pump and fan for heat exchanger to operate the system free of cost.

DISCUSSION

In this study, optimization of the operating parameters to run a solar-based incubation room meant specifically to cater to the fermented dairy product manufacturing unit was undertaken. The objective was to minimize the total energy requirement by such system while maintaining the operating parameters within the specified ranges. Through application of RSM, the optimal combination of operating parameters to effectively and economically run the solar based incubation room were identified. The software recommended fan speed of 3, RH of air 60%, frequency of the hot water pump 42.5 Hz, and adjusting hot water temperature to 68°C. This configuration achieved a desirability of 1.0 and enabled achieving economical total energy consumption of 0.885 kWh per batch (1200 L, 4 hours). By implementing these optimized parameters, the fermented dairy plants can markedly reduce their energy requirement while ensuring ideal conditions required for incubation of cultured milks. We can save Rs. 54600/-per year in operation for 1200 L capacity incubation room and can recover the initial cost of the system in 3 years and 8 months. Utilization of this sort of incubation room in fermented dairy product plants would not only enhance the efficiency of the system but also contribute to sustainability by minimizing energy usage

Overall, our findings demonstrate the effectiveness of employing RSM for optimizing the operating parameters of solar assisted incubation room during maintenance of temperature required during production of fermented milk products in dairy plants.

Conflict of interest: We declare that there is no conflict of interest regarding the present research work.

Author’s contribution: IAC, AGB: Conception and design; AJ, SP: Parameters selection and overall guidance during research; AGB, AJ: Editing the whole manuscript; IAC: Actual research trials performed and prepared manuscript. All authors have approved the final submitted version. All authors approved to submit the article.

Data availability statement: The data set generated during research will be available from the corresponding author on reasonable request.

Ethical approval: The study doesn’t involve any direct research on animals/zebra fish. So, the study doesn’t need to be approved by any authority and the approval statement.

Use of artificial intelligence tools: No Artificial intelligence tool has been used in preparation of manuscript.

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