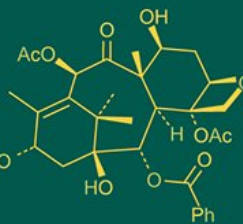
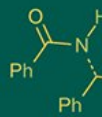


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Optimization of operational parameters for enhancing cooling efficiency of an on-farm vegetable storage structure using response surface methodology

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Abstract

On farm cooling storage structure consisted of main frame, used cellulose pad as a cooling medium, turbo ventilator, exhaust fan for removal of warm air and covered with MS sheets. Tomato, cucumber, okra, and capsicum are kept inside of the structure and performance of the structure was tested. The structure and operational parameters were optimized and the performance evaluation of the structure was also studied on the basis of different response parameters such as cooling efficiency, pad thickness, air flow rate and water application rate. Cost analysis was also carried out. The techno-economic feasibility of the structure was also studied. The optimized input parameters for cooling efficiency were found to be storage structure with pad thickness of $53.09 \approx 50\text{mm}$, air flow rate $1.109 \approx 1 \text{ m}^3/\text{s}$ and water application rate $87.50 \approx 85 \text{ lit/h}$.

Keywords: Cooling storage structure, Cooling efficiency, pad thickness, air flow rate

Introduction

India is the second largest producer of fruits and vegetables after China, according to the Ministry of Agriculture & Farmers Welfare, fruits production in 2024-25 was estimated at 117.65 million tonnes, and vegetable production at 217.80 million tonnes, but wastages about 30%, due to lack of on farm storage facilities (Anonymous, 2026). A wide range of vegetables are grown under India's varying agro-climatic conditions but considerable amount of perishable produce is lost due to poor post-harvest practices. Higher the temperature of handling/storage more is the rate of respiration and other biochemical processes, resulting in more loss of quality and nutritive value. The post-harvest activities at the farm are being done in the open under relatively adverse environmental conditions which in turn enhance post-harvest losses causing fatigue to the persons carrying out these activities. Cold storage facilities cannot be constructed at farm level because of both high investment and operating cost and is not suitable for rural or on-farm storage (Lal Basediya *et al.*, 2013)^[9]. Impact of absence of sufficient storage facilities for fruits and vegetables after being harvested leads to the reduction in the quantity of fruits and vegetables that get to the market which also has an immediate impact on the distribution and consumption of the required amount for the sound living. Refrigerated storage, which is accepted to be the best system for storing the fruits and vegetables in fresh form, is not only energy intensive but also includes enormous capital. In addition, it is not suitable for rural or on-farm storage where the producer would like to store the commodities or only a few days to accumulate sufficient quantities before conveying them to the markets situated far off and in urban regions. Power availability and its cost are additionally major issues, due to which the refrigerated storages for on-farm short duration storage are not recommended. Hence, there is a shift in accentuation in cold storage to other alternative storage systems. An alternative to maintain lower temperature in an enclosed chamber has been a matter of prime significance under Indian condition. Evaporative cooled storage is one such alternative system that has been studied broadly. Evaporative cooling is the simplest and cheapest method for extending shelf life of fruits and vegetables and can also be used as ripening chamber (Bhatnagar *et al.*, 1990; Das and Chandra, 2001; Jha, 2008)^[3, 4, 6].

The evaporative cooled storage structure can be utilized for short-term storage of vegetables, when outside climate is hot and dry. The on-farm cooling storage structures have been found suitable for extending shelf-life of vegetables (Dash and Chandra, 2001; Singh and Satapathy, 2006; Jha, 2008) [11] [6]. This article focusses on the optimization of structure parameters for on farm vegetables cooling storage structure.

Materials and methods

Raw material

The mature tomato, cucumber, capsicum, and okra were procured from local vegetable market and material is used for conducting the storage studies using the developed on farm cooling storage structure.

Cooling wall

Laboratory models of three types of storage structure having different materials such as wood wool, khus and cellulose material as cooling pad were manufactured using mild steel angle sections (25x25x1mm) as shown in Fig.1. The walls of the structure were made by cutting the appropriate size of cellulose pad and fixing over the frame from all the four sides. The other type of walls of the structure was fabricated from mild steel wire mesh with wood wool and khus material fixed over the frame of the structure. The top of the structure was covered with galvanized iron sheet. The fan/turbo ventilator was provided on the roof. Adequate pad surface area is needed to maximize operating efficiency, and an adequate water supply and distribution system.

Water circulation unit

Water cycle of the evaporative cooling system consisted a tank of volume (75lit/h i.e. .600lit/day) 600litres. A 0.3kW centrifugal pump having maximum discharge of 27lit/min and maximum head of 12m was used. PVC pipe having 25mm diameter. Water is pumped from the tank to the mid-length of the distributor through poly ethylene tubes. Waterfalls freely from the distributor onto the pad. Water flow through the cooling pad and falls freely on to the gutter. The gutter is slightly inclined and ends above the water tank. Cellulose pad work on a simple principle of cooling with the help of water. Water flow from top to bottom of the pad and the air is sucked through the cellulose where the air cools down with the help of water, thus the warm air cools down and thus cool the temperature inside the structure.

Exhaust fan

A negative pressure is needed to be created inside the structure which is a function of the pad and the fan, when this happens, air at a positive pressure rush into the system through the pad. For proper air circulation, and the best desired airflow pattern, the fan was located at the central position at the top which now allows air to be drawn from the pad area which in turn draws the cool air and expel the humidified air out. Evaporative air-cooling use very little energy, but most of used for the fan. The axial- flow exhaust fan was fixed at the top of on farm cooling storage structure to control the relative humidity and reduce concentration of carbon dioxide released by stored produce inside the storage structure.

Turbo ventilator

The turbo ventilator works on the principal of natural convection that works to pull the warm air from the structure from lower position commonly through vents. This

rotation gives rise to the centrifugal force which creates vacuum inside of the structure. The turbo ventilators (dia. 30 cm) are provided at two sides of the fan which are needed to withdraw the warm air during the night hours when the fan kept switched off.



Fig 1: On farm cooling storage structure

Performance evaluation of the developed structure

The developed on Farm Cooling Storage Structure was tested as per standard procedures for combination of various treatments. Based on trials, some of the structure and operational parameters such as air flow rate, water application rate and pad thickness were finalized for each crop and were kept constant throughout the complete experimentation.

Optimization of parameters for on farm cooling storage structure

The optimization of the structure parameters such as cooling pad thickness, air flow rate and water application rate was carried out for better cooling efficiency and minimum storage losses. Preliminary trials were conducted in order to fix the levels of Cooling pad thickness, Air flow rate and Water application rate at which better cooling efficiency was obtained. Lab models of on farm cooling storage structure using above three types of pads were manufactured and used for the experimental trials.

Table 1: Level of independent and dependent variables

Independent variables		Dependent variables
Cooling pad thickness, mm	40, 50 and 60	Cooling efficiency, %
Air flow rate, m ³ /s	0.5, 1 and 1.5	
Water application rate, lit/h	50, 75 and 100	

Cooling efficiency

The cooling efficiency was calculated as follows (Bhatnagar *et al.*, 1990) [3],

$$\eta (\%) = \frac{T_{db} - T_s}{T_{db} - T_w} \times 100$$

Where,

T_{db}= dry bulb temperature,

T_w= Wet bulb temperature,

T_s= Storage temperature.

Storage Data Analysis

Response Surface Methodology (RSM) was applied to the experimental data using the package, Design- Expert version 12.0.8.0 (Stat Ease Inc, Minneapolis, MA Trial version, 2020). Structure evaluation: temperature drop, change in relative humidity and cooling efficiency. The treatment combinations of cooling pad thickness, air flow rate and water application rate used for cooling are given in Table 2.

Table 2: Experimental layout for 3 variables and 3 levels response surface analysis

Sr. No.	Cooling pad thickness, mm	Water application rate, lit/h	Air flow rate, m ³ /s	Cooling pad thickness, mm	Air flow rate, m ³ /s	Water application rate, lit/h
	Coded variables			Decoded variables		
	X ₁	X ₂	X ₃	X ₁	X ₂	X ₃
1	0	-1	-1	50	0.5	50
2	-1	-1	0	40	0.5	75
3	0	-1	1	50	0.5	100
4	-1	1	0	40	1.5	75
5	-1	0	-1	40	1	50
6	1	-1	0	60	0.5	75
7	1	0	-1	60	1	50
8	0	0	0	50	1	75
9	0	1	-1	50	1.5	50
10	1	0	1	60	1	100
11	-1	0	1	40	1	100
12	1	1	0	60	1.5	75
13	0	1	1	50	1.5	100
14	0	0	0	50	1	75
15	0	0	0	50	1	75

Results and discussion

Optimization of input parameters for cooling storage structure

The parameters such as cooling pad thickness, air flow rate and water application rate were required to be optimized for maximum cooling efficiency and minimum storage losses.

Effect of input parameters on farm cellulose pad cooling storage structure

The results obtained during the experimentation using the on farm cooling storage structure using cellulose pads are presented in Table 3.1. From Table 3.1, it revealed that the cooling efficiency was observed to be ranging from 82.51 to 92.59 % depending upon the storage treatments. The maximum cooling efficiency was observed in case of treatment having the combination of cooling pad thickness of 50mm and air flow rate of 1m³/s. The minimum cooling efficiency was found for treatment having the combination of pad thickness of 40mm, airflow rate of 1m³/s and water application rate 100 litres/h. The cooling efficiency was found to be dependent on the cooling pad thickness, airflow rate and water application rate. Regarding the effect of independent individual parameter, from analysis of variance (ANOVA) given in Table 3.2, the cellulose cooling pad thickness was having maximum effect followed by air flow rate followed by water application rate on cooling efficiency of the structure. The existence of quadratic terms shows curvilinear nature of response surface graph. The results

Showed that among linear effects of cellulose cooling pad thickness had significant effect on cooling efficiency ($P < 0.01$) at 1% level of significance followed by airflow rate and water application rate. It indicates that increasing the value of variable initially increases the response up to certain level of variable however further increase in the level of variable decreases the value of response.

The cooling efficiency was found to be increased with increase in cellulose pad thickness up to certain limit. Fig. 1a to c shows that as the cellulose pad thickness increased, the cooling efficiency increased up to certain maxima and if cellulose pad thickness is increased beyond this level, the cooling efficiency was observed to be decreased. Significant effect of cellulose pad thickness was observed on cooling efficiency. This might be due to low cooling pad thickness provide less surface area for air water contact or water may flow rapidly if the thickness is less resulted in decreased cooling efficiency (Nada *et al.*, 2019) [10]. The cooling efficiency was found to be increased up to certain level and as the air flow rate increased beyond this level, the cooling efficiency was found to be decreased (Kapilan *et al.*, 2023) [7]. The maximum efficiency was observed for the moderate speed. As the fan speed increases, the cooling efficiency decreases, this may be due to the fact that at higher speed the contact time between the air and the wet surface decreases, results in reduction in effectiveness (Hossein and Farhani, 2021).

Table 3: Cooling efficiency of cellulose pad structure at various treatment combinations

Sr. No.	Cooling Pad Thickness (mm)	Airflow Rate (m ³ /s)	Water Application Rate (lit/h)	Cooling Efficiency (%)
1	50	0.5	50	83.20
2	40	0.5	75	83.08
3	50	0.5	100	85.36
4	40	1.5	75	85.51
5	40	1.0	50	83.84
6	60	0.5	75	84.51
7	60	1.0	50	83.84
8	50	1.0	75	92.59
9	50	1.5	50	83.84
10	60	1.0	100	89.68
11	40	1.0	100	82.51
12	60	1.5	75	89.82
13	50	1.5	100	88.34
14	50	1.0	75	92.59
15	50	1.0	75	91.99

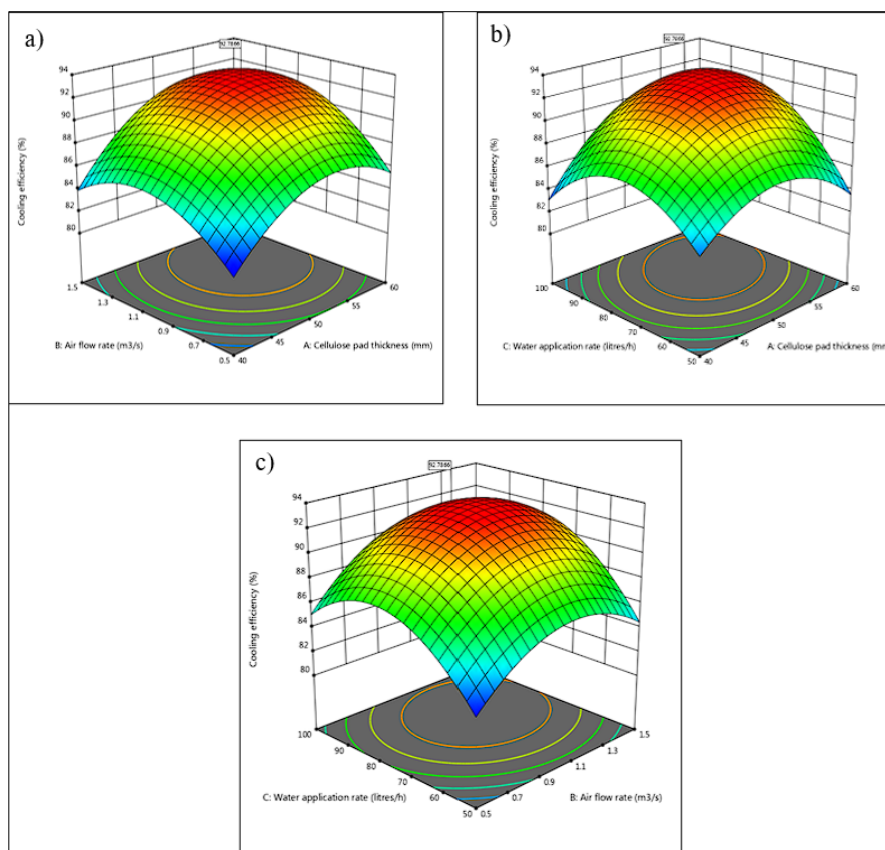


Fig 1: Effect of cellulose pad thickness on cooling efficiency

Table 4: ANOVA for effect of input parameters on cooling efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	190.72	9	21.19	33.25	0.0006	Significant
A- Cellulose pad thickness	20.81	1	20.81	32.65	0.0023	
B- Airflow rate	16.13	1	16.13	25.30	0.0040	
C- Water application rate	15.58	1	15.58	24.45	0.0043	
AB	2.06	1	2.06	3.24	0.1318	
AC	12.85	1	12.85	20.16	0.0065	
BC	1.37	1	1.37	2.15	0.2023	
A ²	43.62	1	43.62	68.45	0.0004	
B ²	38.28	1	38.28	60.07	0.0006	
C ²	58.50	1	58.50	91.79	0.0002	
Residual	3.19	5	0.6373			
Lack of Fit	2.95	3	0.9821	8.18	0.1108	Not significant
Pure Error	0.2400	2	0.1200			
Cor Total	193.91	14				
Std. Dev.	0.7983	R ²	0.9836			
Mean	86.72	Adjusted R ²	0.9540			
C.V.%	0.9206	Predicted R ²	0.7541			
		Adeq Precision	14.4674			

Table 5: Optimization criteria for different process variables and response for cooling efficiency

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Cellulose pad thickness	Is in range	40	60	1	1	3
B: Airflow rate	Is in range	0.5	1.5	1	1	3
Water application rate	Is in range	50	100	1	1	3
Cooling efficiency	Maximize	90.517	92.592	1	1	3

Effect of input parameters for on farm wood wool pads cooling storage structure

The results obtained during the experimentation using wood wool pads are presented in Table 4.1. From Table 4.1, it revealed that the cooling efficiency was observed to be ranging from 79.78 to 85.78 % depending upon the storage treatments. The maximum cooling efficiency was observed

in case of treatment having the combination of cooling pad thickness of 40 mm, air flow rate of 1m³/s and water application rate of 100 lit/h. The minimum cooling efficiency was found for treatment having the combination of pad thickness of 50 mm, airflow rate of 0.5m/s and water application rate 50 litres/h. The cooling efficiency was found to be dependent on the cooling pad thickness, airflow

rate and water applications rate. The data for cooling efficiency were analysed for stepwise regression analysis and the analysis of variance (ANOVA) is shown in Table 4.2. The results showed that among linear effects of air flow rate had significant effect on cooling efficiency ($P < 0.01$) at 1% level of significance followed by water application rate and cooling pad thickness. It indicates that increasing the value of variable initially increases the response up to certain level of variable however further increase in the level of variable decreases the value of response. The effect of wood wool pad thickness and airflow rate on cooling efficiency is shown in Fig. 2a to 2c. The cooling efficiency was found to be increased with increase in wood wool pad thickness upto certain limit. Fig. 2a to 2c shows that as the

wood wool pad thickness increased, the cooling efficiency increased upto certain maxima and if wood wool pad thickness is increased beyond this level, the cooling efficiency was observed to be decreased (Nada *et al.*, 2019)^[10]. Significant effect of airflow rate and water application rate was observed on cooling efficiency. This might be due to increase in thickness, the efficiency decreases because it restricts the flow of air due to its high density. Fig. 2a to 2c shows that as the airflow rate increased, the cooling efficiency was found to be increased upto certain level and as the airflow rate increased beyond this level, the cooling efficiency was found to be decreased (Hossein and Farhani, 2021).

Table 6: Cooling efficiency of wood wool pad structure at various treatment combination

Sr. No.	Cooling pad thickness, mm	Airflow rate, m ³ /s	Water application rate, lit/h	Cooling efficiency, %
1	50	0.5	50	79.78
2	40	0.5	75	80.32
3	50	0.5	100	80.35
4	40	1.5	75	84.74
5	40	1	50	81.19
6	60	0.5	75	82.27
7	60	1	50	83.33
8	50	1	75	83.73
9	50	1.5	50	80.76
10	60	1	100	83.33
11	40	1	100	85.78
12	60	1.5	75	83.84
13	50	1.5	100	83.44
14	50	1	75	85.45
15	50	1	75	85.47

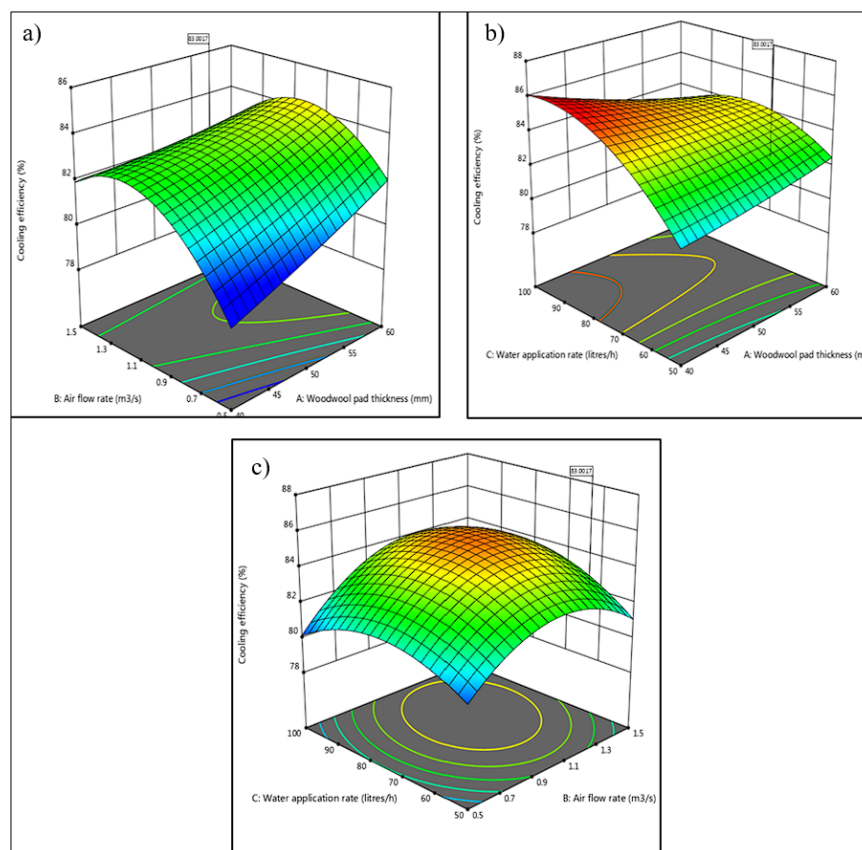


Fig 2: Effect of wood wool pad thickness on cooling efficiency

Table 7: ANOVA for effect of input parameters on cooling efficiency

Source	Sum of Squares	Df	Mean Square	F-value	P-value	Remark
Model	54.85	9	6.09	10.47	0.0093	Significant
A-Wood wool pad thickness	0.0686	1	0.0686	0.1178	0.7454	
B-Airflow rate	12.63	1	12.63	21.70	0.0055	
C-Water application rate	7.69	1	7.69	13.22	0.0150	
AB	2.03	1	2.03	3.49	0.1208	
AC	5.28	1	5.28	9.06	0.0297	
BC	1.11	1	1.11	1.92	0.2250	
A ²	0.0511	1	0.0511	0.0878	0.7789	
B ²	17.94	1	17.94	30.83	0.0026	
C ²	9.37	1	9.37	16.10	0.0102	
Residual	2.91	5	0.5820			
Lack of Fit	0.9169	3	0.3056	0.3067	0.8231	Not significant
Pure Error	1.99	2	0.9966			
Cor Total	57.76	14				
Std. Dev.	0.7629	R ²	0.9496			
Mean	82.92	Adjusted R ²	0.8589			
C.V.%	0.9200	Predicted R ²	0.6684			
		Adeq Precision	9.7415			

Table 8: Optimization criteria for different process variables and response for cooling efficiency

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Woodwool pad thickness	Is in range	40	60	1	1	3
B: Air flow rate	Is in range	0.5	1.5	1	1	3
Water application rate	Is in range	50	100	1	1	3
Cooling efficiency	Maximize	79.7869	85.7843	1	1	3

Effect of input parameters for on farm khus pads cooling storage structure

The results obtained during the experimentation using the on farm cooling storage structure using khus pads are presented in Table 5.1. From Table 5.1, it revealed that the cooling efficiency was observed to be ranging from 80.35 to 87.03 % depending upon the storage treatments. The maximum cooling efficiency was observed in case of treatment having the combination of khus cooling pad thickness of 50 mm, air flow rate of 1 m³/s and water application rate of 75 lit/h. The minimum cooling efficiency was found for treatment having the combination of khus pad thickness of 50 mm, air flow rate of 0.5 m/s and water application rate 50 litres/h. The cooling efficiency was found to be dependent on the, air flow rate, water applications rate and khus cooling pad thickness. The data for cooling efficiency were analysed for stepwise regression analysis and the analysis of variance (ANOVA) is shown in Table 5.2. The results showed that among linear effects of air flow rate had significant effect on cooling efficiency (P<0.01) at 1 % level of significance

followed by water application rate and cooling pad thickness. It indicates that increasing the value of variable initially increases the response up to certain level of variable however further increase in the level of variable decreases the value of response. The effect of khus pad thickness and air flow rate on cooling efficiency is shown in Fig. 3a to 3c. The cooling efficiency was found to be increased with increase in khus pad thickness up to certain limit. Fig. 3a to 3c shows that as the khus pad thickness increased, the cooling efficiency increased up to certain maxima and if khus pad thickness is increased beyond this level, the extraction efficiency was observed to be decreased (Khater, 2022) [8]. Significant effect of air flow rate and water application rate was observed on cooling efficiency. Fig. 3a to 3c shows that as the khus pad thickness, air flow rate and water application rate increased, the cooling efficiency was found to be increased up to certain level and as the levels increased beyond this level, the cooling efficiency was found to be decreased (Tejero-González and Franco-Salas, 2021) [1].

Table 9: Cooling efficiency of khus pad structure at various treatment combinations

Sr. No.	Cooling Pad Thickness (mm)	Airflow Rate (m ³ /s)	Water Application Rate (lit/h)	Cooling Efficiency (%)
1	50	0.5	50	80.35
2	40	0.5	75	81.66
3	50	0.5	100	82.64
4	40	1.5	75	85.36
5	40	1.0	50	81.66
6	60	0.5	75	83.20
7	60	1.0	50	84.50
8	50	1.0	75	86.84
9	50	1.5	50	83.20
10	60	1.0	100	85.71
11	40	1.0	100	86.65
12	60	1.5	75	86.20
13	50	1.5	100	85.51
14	50	1.0	75	86.84
15	50	1.0	75	87.03

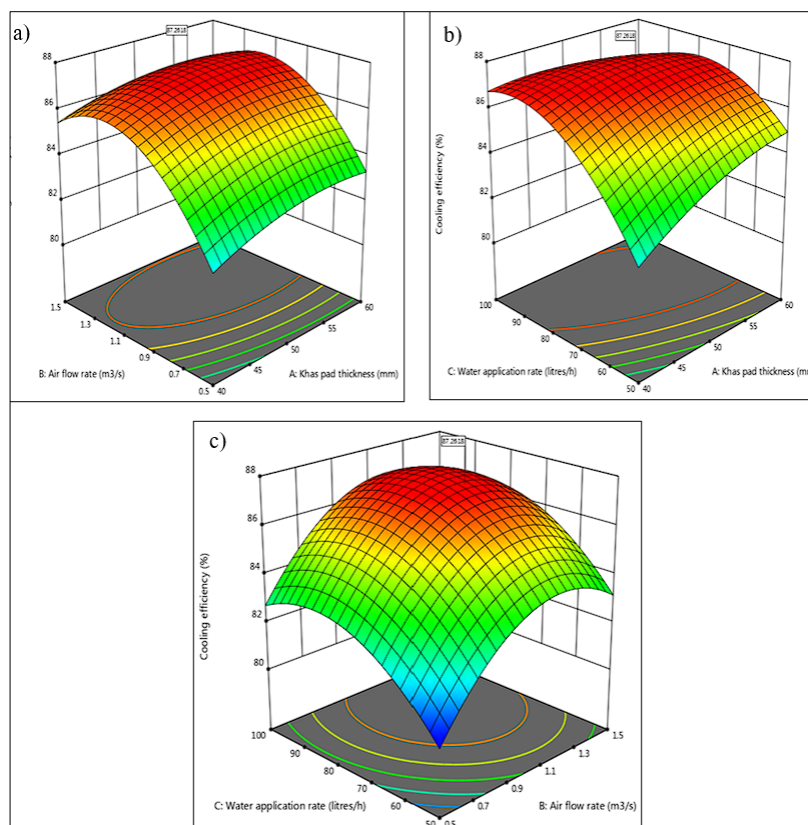


Fig 3: Effect of khus pad thickness on cooling efficiency

Table 10: ANOVA for effect of input parameters on cooling efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	67.80	9	7.53	76.70	<0.0001	Significant
A – Woodwool Pad Thickness	2.29	1	2.29	23.33	0.0048	Significant
B – Air Flow Rate	19.29	1	19.29	196.36	<0.0001	Significant
C – Water Application Rate	14.56	1	14.56	148.25	<0.0001	Significant
AB	0.1223	1	0.1223	1.25	0.3151	Not Significant
AC	3.57	1	3.57	36.39	0.0018	Significant
BC	0.0001	1	0.0001	0.0013	0.9728	Not Significant
A ²	1.11	1	1.11	11.28	0.0201	Significant
B ²	18.73	1	18.73	190.65	<0.0001	Significant
C ²	11.02	1	11.02	112.23	0.0001	Significant
Residual	0.4911	5	0.0982	–	–	–
Lack of Fit	0.4674	3	0.1558	13.17	0.0714	Not Significant
Pure Error	0.0237	2	0.0118	–	–	–
Cor Total	68.29	14	–	–	–	–
Std. Dev.	0.3134	R ²	0.9928	–	–	–
Mean	84.50	Adjusted R ²	0.9799	–	–	–
C.V. (%)	0.3709	Predicted R ²	0.8897	–	–	–
Adeq Precision	26.8712	–	–	–	–	–

Table 11: Optimization criteria for different process variables and response for cooling efficiency

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Khus Pad Thickness	Is in range	40	60	1	1	3
B: Airflow Rate	Is in range	0.5	1.5	1	1	3
C: Water Application Rate	Is in range	50	100	1	1	3
Cooling Efficiency	Maximize	80.3571	87.0370	1	1	3

Table 12: Optimized solution generated by the software for cooling efficiency

Sr. No.	Cellulose, wood wool and khus pad thickness, mm	Airflow rate, m ³ /s	Water application rate, litres/h	Cooling efficiency, %	Desirability	
1.	53.090	1.109	87.808	92.78	1.00	Selected
2.	40.519	1.059	93.148	85.81	1.00	Selected
3.	47.665	1.245	91.699	87.27	1.00	Selected

Verification of the model for cooling efficiency

Experiments were carried out for cooling efficiency was carried out at optimized input parameters (Cellulose pad thickness = 53.09 $\approx$ 50mm, airflow rate = 1.10 $\approx$ 1m³/sand water application rate 87.80 lit/h $\approx$ 85), (Wood wool pad thickness = 40.51 $\approx$ 40 mm, air flow rate = 1.059 $\approx$ 1m³/s and water application rate 93.148 lit/h) and (Khus pad thickness = 47.66 $\approx$ 50 mm, airflow rate= 1.24 $\approx$ 1.20 m³/sand water application rate 91.69 lit/h) for testing the adequacy of model equations for predicting the cooling efficiency response values.

Table 13: Predicted and experimental values of response at optimum process conditions for cooling efficiency

Sr. No	Cooling pad	Response	Predicted value	Experimental value	$\pm$ SD
1.	Cellulose	Cooling efficiency,%	92.59	93.89*	$\pm$ 1.49
2.	Wood wool	Cooling efficiency,%	85.81	86.59*	$\pm$ 1.29
3.	Khus	Cooling efficiency,%	87.27	88.39*	$\pm$ 1.04

The observed experimental values (mean of three experiments) and values predicted by the equations of the model are presented in Table 7. The experimental values were found to be very close to the predicted values for cooling efficiency.

Conclusion

Optimized input parameters for maximum cooling efficiency inside storage structure were found to be cooling pad having thickness 50 mm, water application rate 85 lit/hr and air flow rate 1 m³/s. On the basis of experimental trials, the cellulose pad structure was found to have better water holding capacity and maximum cooling efficiency compared to other two materials. Also, the storage losses during trials in laboratory models were found to be minimum using cellulose pad cooling storage structure.

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