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APPENDIX- A

Table A1 The statistical fit parameters of ginger drying in OSD

S. No	Model name	Coefficients and constants	R^2	χ2	RMSE
1	Newton	k = 0.13612	0.98422	0.00125	0.04087
2	Page	k = 0.08225, n = 1.22842	0.99998	0.00021	0.00258
3	Modified Page	k = 0.03689, n = 3.68897	0.98889	0.00105	0.03041
4	Henderson and Pabis	a = 1.0618, k = 0.14387	0.99199	0.00256	0.02115
5	Logarithmic	a = 1.08283, k = 0.12798, c = -0.04095	0.99923	0.00230	0.00981
6	Midilli and Kucuk	a = 0.9848, k = 0.07737, n = 1.246, b = -0.0001419	0.99589	0.00381	0.01122
7	Wang and Singh	a = -0.09089, b = 0.00201	0.98873	0.00101	0.03041
8	Diffusion approach	a = 0.98266, b = 1, k = 0.13608	0.98784	0.00109	0.03041
9	Two Term	a = 0.53088, b = 0.53088, k1= 0.14386, k2 = 0.14386	0.99125	0.00253	0.02115
10	Two Term exponential	a =1.7736, k = 0.18612	0.99882	0.00029	0.00304

Table A2 The statistical fit parameters of ginger drying in ISGHD

S. No	Model name	Coefficients and constants	R^2	χ2	RMSE
1	Newton	k = 0.13332	0.99842	0.00097	0.06542
2	Page	k = 0.08306, n = 1.22321	0.99978	0.00013	0.00258
3	Modified Page	k = 0.03651, n = 3.65127	0.98578	0.00138	0.02339
4	Henderson and Pabis	a =1.05478, k = 0.14072	0.98998	0.00245	0.01654
5	Logarithmic	a =1.1718, k = 0.10332, c = -0.15263	0.99912	0.00025	0.00148
6	Midilli and Kucuk	a = 0.99367, k =0.08591, n = 1.17517, b =-0.00192	0.99788	0.00120	0.00314
7	Wang and Singh	a = -0.10215, b = 0.00276	0.98689	0.00136	0.02339
8	Diffusion approach	a = 1, b = 1, k = 0.13334	0.98426	0.00146	0.02339

9	Two Term	a = 0.5272, b = 0.5272, k1 = 0.14072, k2 = 0.14072	0.98813	0.00116	0.01654
10	Two Term exponential	a = 1.7648, k = 0.18464	0.99828	0.00068	0.00271

Table A3 The statistical fit parameters of ginger drying in TD

S. No	Model name	Coefficients and constants	R^2	χ2	RMSE
1	Newton	k = 0.14823	0.99447	0.00046	0.09447
2	Page	k = 0.08813, n = 1.24603	0.99949	0.00016	0.00264
3	Modified Page	k = 0.03852, n = 3.85012	0.98577	0.00136	0.03123
4	Henderson and Pabis	a = 1.06151, k = 0.15668	0.98971	0.00332	0.02258
5	Logarithmic	a = 1.1036, k = 0.13032, c = -0.07034	0.99891	0.00041	0.00819
6	Midilli and Kucuk	a = 0.98555, k = 0.08484, n =1.24486, b= -0.00068	0.99658	0.00366	0.00717
7	Wang and Singh	a= -0.10356, b=0.00267	0.98637	0.00133	0.03123
8	Diffusion approach	a = 0.89211, b = 1, k = 0.14641	0.98516	0.00142	0.03115
9	Two Term	a = 0.53076, b = 0.53076, k1 = 0.15667, k2 = 0.15667	0.98874	0.00108	0.02258
10	Two Term exponential	a = 1.7893, k = 0.20451	0.99843	0.00062	0.00344

Table A4 The statistical fit parameters of ginger drying in RWD

S. No	Model name	Coefficients and constants	R^2	χ2	RMSE
1	Newton	k = 0.14234	0.99684	0.00056	0.08561
2	Page	k =1.23554, n = 0.08732	0.99936	0.00024	0.00315
3	Modified Page	k = 0.03278, n = 3.78251	0.97897	0.00561	0.02875
4	Henderson and Pabis	a =1.06783, k = 0.13876	0.97451	0.00412	0.02456
5	Logarithmic	a =1.0156, k = 0.13251, c = -0.08452	0.99987	0.00032	0.00845
6	Midilli and Kucuk	a = 0.99854, k = 0.08974, n = 1.23578, b = -0.00023	0.98965	0.00258	0.00153

7	Wang and Singh	a = -0.10258, b = 0.00237	0.97642	0.00021	0.00215
8	Diffusion approach	a = 0.92432, b =1, k = 0.13457	0.98745	0.00215	0.03017
9	Two Term	a = 0.53156, b = 0.53156, k1= 0.15231, k2= 0.15231	0.98845	0.00214	0.01321
10	Two Term exponential	a =1.6926, k = 0.21561	0.99745	0.00021	0.00294

Table A5 Average rate of energy input (W), energy output (W), energy loss (W) for SAH

Air flow rate kg/s	Energy input (W)	Energy output (W)	Energy loss (W)
0.0067 (Natural)	208-511	134-341	74-169
0.012	211-517	160-388	50-129
0.018	175-511	136-361	49.38-110
0.024	107-506	113-355	23.75-151

Table A6 Average rate of energy input (W), energy output (W), energy loss (W) for ISGHD system

Air flow rate kg/s	Energy input (W)	Energy output (W)	Energy loss (W)
0.0067 (Natural)	198-490	140-374	58-116
0.012	195-510	148-412	47-98
0.018	197-493	143-387	54-87
0.024	200-480	142-375	45-105

Table A7 Average rate of exergy input (W), exergy output (W), exergy loss (W) for ISGHD system

Air flow rate kg/s	Exergy input (W)	Exergy output (W)	Exergy loss/useful (W)
0.0067 (Natural)	34-134	3-31	32-106
0.012	31-144	6-45	25-98
0.018	22-149	3-49	21-100
0.024	34-154	8-45	27-108

APPENDIX- B

B1 Environmental Analysis

Energy payback time (EPBT)

$$Energy\ payback\ time\ (EPBT) = \frac{Embodied\ Energy(kWh)}{Annual\ Energy\ Output(kWh/year)}$$

$$Daily\ thermal\ output\ Q_{ev} = \frac{Moisture\ evaporated\ , m_w(kg) \times\ latentheat, \lambda\ (J/kg)}{3.6 \times 10^6}$$

$$Daily\ thermal\ output\ Q_{ev} = \frac{3.27 \times\ 2.26 \times 10^6}{3.6 \times 10^6}$$

$$Daily\ thermal\ output\ Q_{ev} = 2.05\ kW\text{h}$$

$$Annual\ energy\ output = Daily\ thermal\ output\ Q_{ev} \times No\ of\ sunshine\ days$$

$$Annual\ energy\ output = 2.05kWh \times 250$$

$$Annual\ energy\ output = 513.6\ \ kWH$$

$$Energy\ payback\ time\ (EPBT) = \frac{1199.442\ kWh}{Annual\ Energy\ Output}$$

$$Energy\ payback\ time\ (EPBT) = \frac{1199.442\ kWh}{513.6\ \ kWH/year}$$

$$Energy\ payback\ time\ (EPBT) = \ 2.33\ year$$

Carbon dioxide emitted by the ISGHD

$$CO_2\ emmission\ per\ year = \frac{Embodied\ Energy\ \times 0.98}{lifetime}$$

$$CO_2\ emmission\ per\ year = \frac{1199.442\ \times 0.98}{3}$$

$$CO_2\ emmission\ per\ year = \ 470.18$$

CO_2 mitigation by ISGHD

$$CO_2\ mitigation\ (kWh/year) = \frac{1}{1 - Lda} \times \frac{1}{1 - Ldt} \times 0.98$$

$$CO_2\ mitigation\ (lifetime) = \ Embodied\ Energy\ \times 2.042$$

$$CO_2\ mitigation\ (lifetime) = 1199.442\ \times 2.042$$

$$CO_2\ mitigation\ (lifetime) = 2449\ \text{kg}$$

Carbon credit earned by dryer

$$Net\ Carbon\ Mitigation$$
$$= Annual\ energy\ output\ energy \times life\ time \times 2.042$$
$$- Embodied\ energy$$

$$Net\ Carbon\ Mitigation = 513.6 \times 2.5 \times 2.042 - 1199.442$$

$$Net\ Carbon\ Mitigation = 1422 \text{ kg}$$

$$Earned\ carbon\ credit = Net\ CO_2\ mitigation \times price\ per\ ton\ of\ CO_2\ mitigation$$

$$Earned\ carbon\ credit = 1.422 \times 3750$$

$$Earned\ carbon\ credit = 5{,}332 \text{ INR}$$

B2 Economic Analysis

$$Energy\ requirement\ of\ SGHD\ per\ day\ per\ batch = m\ \times cp \times \Delta T$$

$$Energy\ requirement\ of\ SGHD\ per\ day\ per\ batch = 4\ \times 3.3 \times (55 - 27)$$

$$Energy\ requirement\ of\ SGHD\ per\ day\ per\ batch = 370\ kJ$$

$$Energy\ requirement\ of\ SGHD\ per\ day\ per\ batch = 0.1024\ kWh$$

$$Energy\ requirement\ per\ kg\ (kWh) = \frac{0.1024}{4} = 0.0256\ \ kWh$$

$$Total\ Anuual\ Consumption(kWh) = 0.1024 \times 190 = 19.456\ kWh$$

$$Annual\ energy\ cost = 19.456 \times 6 = 116.736\ INR$$

$$The\ specific\ cost\ of\ drying\ per\ kg = \frac{116.736}{4} = 29.184\ \ INR$$

Annual cost of dryer C_a has been calculated as given as

$$C_a = C_{ac} + C_m - S_v + C_{acf}$$

C_{ac} is the annual capital cost, C_m is the maintenance cost, S_v is the salvage value and C_{acf} is annual operational cost of fan

$$C_{ac} = C_c \times F_{cp}$$

C_c is the capital cost and F_{cp} rate of interest on the capital cost

$$C_{ac} = 6235 \times \frac{d(1+d)^n}{(1+d)^n - 1}$$

$$C_{ac} = 6235 \times \frac{0.08(1+0.08)^1}{(1+0.08)^1 - 1}$$

$$C_{ac} = 6733\ INR$$

Now, the salvage value S_v can be calculated using the formula.

$$S_v\ = C_c \times (1-i)^n$$

$$S_v = 6235 \times (1 - 0.06)^3$$

$$S_v = 4791$$

Where, i is depreciation rate (6 %), n is age in years.

$$C_m = C_{ac} \times 0.03$$

$$C_m = 202$$

$$\mathrm{C_{acf}} = \mathrm{N_f} \times \mathrm{P_f} \times \mathrm{P_e}$$

The fan is operated solar panel, so cost is zero no outsource electricity is involved.

$$\text{Annual cost of dryer } \mathrm{C_a} = 6733 + 202 - 673.3 + 0$$

$$\text{Annual cost of dryer } \mathrm{C_a} = 6261.7$$

APPENDIX- C

Publications, Participations and Recognitions from the Outcomes of the Research

C1 List of Publication

1. Choudhary, A. K., & Hazarika, M. K. Modelling and thermal analysis of an integrated solar greenhouse dryer for ginger (*Zingiber officinale*) and product quality. *Journal of Stored Products Research*, 106:102313, 2024.

2. Choudhary, A. K., Chakraborty, S., Kumari, S., & Hazarika, M. K. Feed forward neural network and its reverse mapping aspects for the simulation of ginger drying kinetics. *Agricultural Engineering International*: CIGR Journal, 24(1): 2022.

C2 List of presented paper in conference

1. Presented paper in the International Conference on Emerging Technologies in Food Processing-III (ETFP-2023) "Exergo-economic and environmental analysis of sustainable integrated solar greenhouse dryer for ginger drying" organized by the Department of Food Processing Technology, GKCIET, Malda, West Bengal during 26th -27th Sept 2023.

2. Presented paper in the International Conference on Emerging Technologies in Food Processing-II (ETFP-2022) "Experimental studies on drying characteristics of ginger under solar greenhouse drying assisted with SAH" organized by the Department of Food Processing Technology, GKCIET, Malda, West Bengal during 25th -26th March 2022.

3. Presented paper in the international conference on Sustainable Approaches in Food Engineering and Technology (SAFETY 2022) "Experimental study on drying kinetics for ginger using integrated solar greenhouse dryer in North-East Region of India organized by the Department of Food Engineering and Technology, Tezpur university and Department of soil, water and Agricultural Engineering, Sultan Qaboos University, Oman at 19th -20th October 2022.

4. Presented paper in the international conference on Sustainable Approaches in Food Engineering and Technology (SAFETY 2021)" impact of solar greenhouse drying on agricultural product" organized by the Department of Food Engineering and Technology, Tezpur university and University of Georgia, Georgia, US at June 24th -25th 2021.

C3 Awards and recognition to the outcome of the present work

1. 1st position in the Oral presentation in the International Conference on "Emerging Technologies in Food Processing-III (ETFP-2023)" organized by the Department of Food Processing Technology, GKCIET, Malda, West Bengal during 26th -27th Sept 2023.
2. 2nd position in the poster presentation on International Conference on "Sustainable Approaches in Food Engineering and Technology (SAFETY 2022)" organized by the Department of Food Engineering and Technology, Tezpur university and Department of soil, water and Agricultural Engineering, Sultan Qaboos University, Oman at 19th -20th October 2022.

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Development of an Integrated Solar Greenhouse Dryer and Performance Evaluation for Ginger Drying in Northeastern Region of India

A thesis submitted in part fulfilment of the requirements for award of the degree of

Doctor of Philosophy

Submitted by

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