NATTO MOISTURE CONTENT HOMOGENEITY IMPROVEMENT VIA CONTAINING TRAYS TOPOLOGY MODIFICATION IN HEAT PUMP DRYER

CẢI THIỆN ĐỘ ĐỒNG ĐỀU ĐỘ ẨM HẠT NATTO THÔNG QUA HIỆU CHỈNH CẤU HÌNH KHAY SẤY TRONG MÁY SẤY BƠM NHIỆT

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ABSTRACT

Several experiments were conducted in a drying chamber, with Natto as the test material. These experiments involved varying the number of trays and the angle of the trays to determine the most appropriate configuration, verify the uniformity of air distribution in the equipment, and evaluate the uniformity of the average moisture reduction of Natto seeds in each batch compared to the established theory in the previous study.

Keywords: *Experiment, Natto seed, heat pump dryer.*

TÓM TẮT

Một số thực nghiệm đã được tiến hành trong buồng sấy, với Natto làm vật liệu thử nghiệm. Các thực nghiệm này liên quan đến việc thay đổi số lượng khay và góc của các khay để xác định cấu hình phù hợp nhất, xác minh tính đồng nhất của phân phối không khí trong thiết bị và đánh giá tính đồng nhất của mức giảm độ ẩm trung bình của hạt Natto trong mỗi mẻ so với mẻ đã thiết lập. lý thuyết trong nghiên cứu trước.

Từ khóa: *Thực nghiệm, hạt Natto, máy sấy bơm nhiệt.*

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1. INTRODUCTION

The drying process is mainly affected by two factors of drying air: velocity and temperature. A study conducted by HAT Norhaida et al. [1] using heat pump equipment to dry Clinacanthus nutans showed that as air temperature increases, drying time decreases. The increase in air velocity also heavily affects the drying time (415, 370, 320, and 275 minutes at the air velocity of 0.5, 1.0, 1.5, and 2.0m/s, respectively) [2]. The appropriate air velocity for moisture removal depends on the type of material. For Bermuda grass, an air velocity of 2m/s results in higher moisture removal rates compared to velocities of 2.5m/s and 1.5m/s [3].

Natto, a traditional Japanese food made from fermented soybeans, has a limited shelf life and needs to be dried to preserve its nutritional value [4]. The most suitable drying methods for Natto are heat pump and vacuum drying. Both have advantages such as high energy efficiency, better product quality, and no damage caused by high temperatures [5,6]. Heat pump drying equipment is used due to the high cost of vacuum drying equipment. However, non-uniform air distribution in the heat pump dryer negatively affects the final product quality [7]**.** Therefore, this study tunes the dryer configuration to improve air uniformity as well as control the air velocity and temperature that go through the material.

2. MATERIALS AND METHOD

All experiments at an industrial scale were conducted at Mangala Biotechnology and Trading Co., Ltd., located at 264 Ngoc Thuy Street, Ngoc Thuy Ward, Long Bien District, Hanoi.

2.1. Materials

Fermented soybeans (Natto) are stored at below 4^{o}C because of thermal sensitivity before heat pump drying at 55ºC to preserve nutritional values and bioactivity. The shape of Natto seeds is ellipsoid, whose smallest dimension is bigger than 8mm. The structure of Natto seeds is porous. Their average value of moisture content is 70 (w.b).

Natto seeds at more than 30 (w.b) can be damaged at ambient conditions in one day because of biological transfer, so the drying process has to decrease the moisture content of all Natto seeds to less than 30 (w.b) in one day. The air distribution in the drying chamber must be rather uniform to ensure the moisture content homogeneity of Natto seeds in each tray. The product on each tray must have an average moisture content of less than 18 to be ground and pelletized.

2.2. Experiment equipment

The equipment used in the experiment is the same type and dimension as the one that was simulated in the study by Nguyen Duc Trung et al. [8]. The Figure 1 shows the experiment equipment.

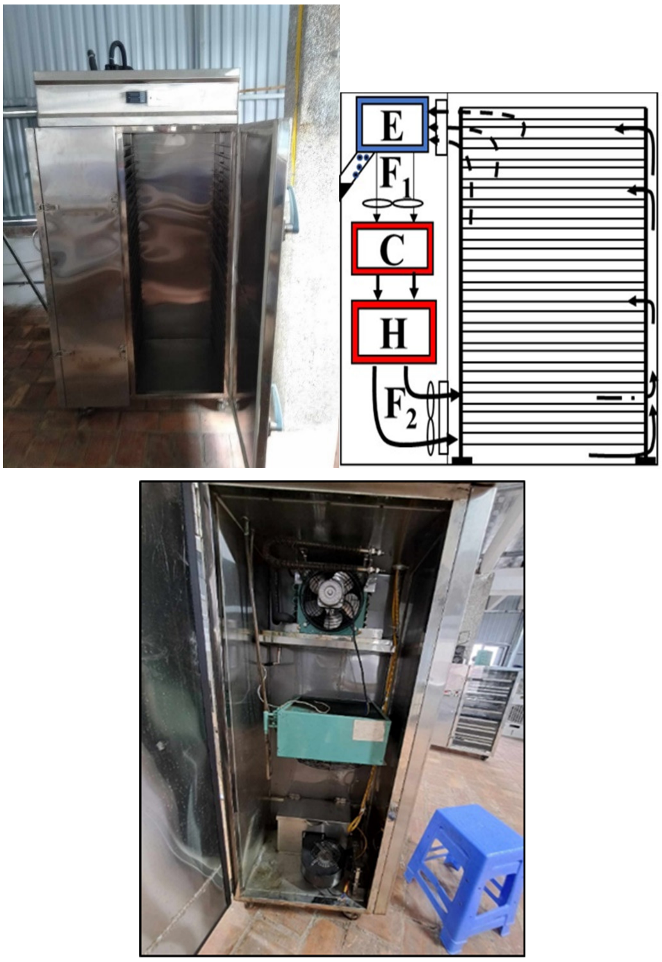


Figure 1. Pilot-scale equipment

The notations E, F, C, and H corresponding represent the evaporator, fan, condenser, and heater. The equipment capacity is 100kg per batch. The heat pump system has a compressor capacity of 1.1kW, a condenser of 4.2kW, and an evaporator of 3.1kW, with a coefficient of performance (COP) of 3.

Air velocity through the inlet is 10m/s. A thermostat is used to control the drying air temperature. The thermostat reads the air temperature and automatically turns on or off the heater if the air temperature does not reach 55ºC, with an allowable temperature error of 2ºC (due to system delay). Several experiments are conducted to find the configuration for the chamber with the most uniform product moisture and to ensure that the product is not damaged.

2.3. Experimental procedure and product homogeneity evaluation

After conducting three experiments for each configuration, the presented results show their average. For the initial configuration of 25 trays, each i^{th} tray is set on the line which connects from "i"L to "i"R horizontally. Table 1 and Figure 2 display the position of trays in the two improved configurations. The tray is set skewed on the line from iL to (i+1)R or (i+2)R.

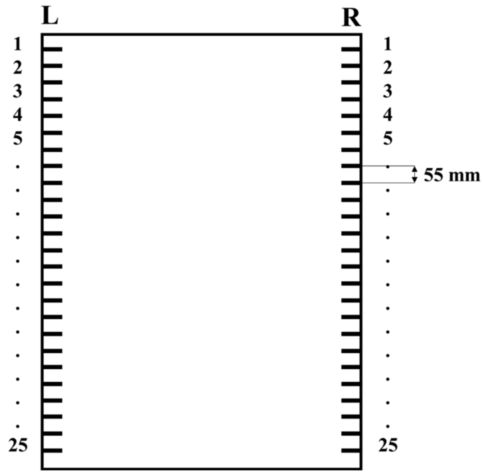


Figure 2. Trays place position

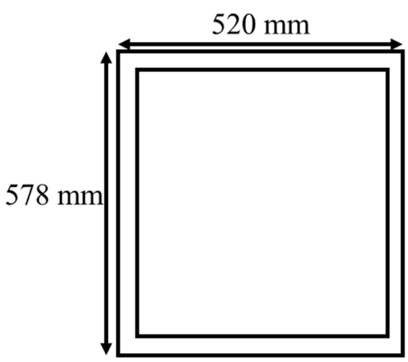
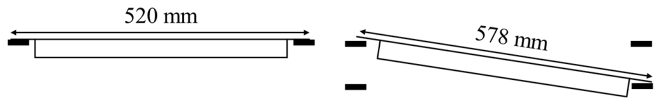


Figure 3. Tray dimension

Table 1. Tray position in each configuration

1st improved configuration				2nd improved configuration			
Nº/Air shield	Position	Nº/Air shield	Position	Nº/Air shield	Position	Nº/Air shield	Position
1	3L-4R	8	12L-13R	1	3L-4R	8	12L-14R
2	4L-5R	9	14L-15R	2	4L-5R	9	14L-16R
3	5L-6R	10	16L-17R	3	5L-6R	10	16L-17R
4	6L-7R	11	17L-18R	4	6L-7R	11	17L-18R
5	8L-9R	12	18L-19R	5	8L-10R	12	18L-19R
6	9L-10R	13	19L-20R	6	9L-11R	13	19L-20R
7	11L-12R	Air shield 1	1L-3R	7	11L-13R	Air shield 1	1L-3R
		Air shield 2	21L-21R			Air shield 2	21L-21R



a) 25 - tray configuration b) 13 - tray configuration

Figure 4. Tray place difference configuration

Each experiment uses 35.5 kilograms of material and 55ºC drying air temperature, and the number of trays and tray angles are tuned. The trays are weighed and numbered, and each tray has approximately material weight. The drying process stops when the average moisture content on each tray is lower than 17% or all the material causes damage in the drying process. When the material in one tray has not reached 30% moisture content in one day, this tray is loaded out, and the empty tray is placed back in the equipment to ensure air uniformity.

Each tray's weight changes are tracked every 24 hours throughout the drying process. To calculate the weight of Natto seeds on each tray, use the following formula:

$$m_{mat} = m - m_t \quad (1)$$

The weight of materials during the drying process is represented by m_{mat}, while m represents the weight of the contained material tray, and m_t represents the weight of the empty tray. The formula for calculating the average moisture content of the Natto seeds (w.b) on each tray during the drying process:

$$u\% = \frac{m_{mat} - m_{drym}}{m_{mat}} \quad (2)$$

where u% is the average moisture content of the material (AMCOM) on each tray in the drying process (g); m_{mat} is the weight of the material in the drying process (g); m_{drym} is the dry matter weight (g).

The following criteria to evaluate the product moisture homogeneity:

$$u\%_a = \frac{\sum u\%_i}{N} \quad (3)$$

$$S_u = \sqrt{\frac{\sum (u\%_i - u\%_a)^2}{N}} \quad (4)$$

$$S_{\%} = \frac{S_u}{u\%_a} \quad (5)$$

The lower the S_u and S, the higher the uniformity of the product moisture after the drying process. The decreasing in value $u\%_a$ means that the AMCOM on each tray tends to decrease.

3. RESULT AND DISCUSSION

The Tables 2, 3 and 4 show the weight and AMCOM on each tray of the 25, 18, and 13-tray configurations every 24 hours during the experiment. The damaged material is removed, and the empty tray is put back to ensure proper air distribution.

Table 2. The AMCOM on each tray in 25 trays configuration (Case 1)

Hrs / Nº	0 (hr)		24 (hrs)		48 (hrs)		72 (hrs)	
	m(g)	u%	m(g)	u%	m(g)	u%	m(g)	u%
1	1420	70%	743	43%	603	29%	523	19%
2	1422	70%	626	32%	518	18%	498	14%
3	1421	70%	644	34%	524	19%	505	16%
4	1421	70%	849	50%	689	x	566	x
5	1420	70%	932	54%	747	x	624	x
6	1421	70%	985	57%	782	x	648	x
7	1420	70%	1037	59%	809	x	664	x
8	1420	70%	1052	60%	827	x	686	x
9	1420	70%	1056	60%	846	x	706	x
10	1421	70%	1060	60%	850	x	713	x
11	1420	70%	1060	60%	852	x	717	x
12	1420	70%	1062	60%	855	x	722	x
13	1420	70%	1065	60%	865	x	732	x
14	1422	70%	1067	60%	869	x	736	x
15	1420	70%	1062	60%	868	x	738	x
16	1419	70%	1059	60%	865	x	730	x
17	1420	70%	1052	60%	859	x	720	x
18	1420	70%	995	57%	811	x	684	x
19	1420	70%	975	56%	786	x	663	x

20	1422	70%	963	56%	770	x	642	x
21	1420	70%	951	55%	726	x	603	x
22	1420	70%	754	44%	605	x	514	x
23	1421	70%	635	33%	534	20%	508	16%
24	1420	70%	625	32%	523	19%	493	14%
25	1422	70%	599	29%	497	14%	480	11%

After 24 hours of 1st configuration experiment, almost all trays have not reached the desired AMCOM. In the next 24 hours, all of the material is damaged. The case 25 trays are stopped at 48 hours. Three criterion are not calculated in this case because just 6 out of 25 trays have material at the end of the drying process.

Table 3. The AMCOM on each tray in first improved configuration (Case 2)

Hrs / Nº	0 (hr)		24 (hrs)		48 (hrs)		72 (hrs)		96 (hrs)		120 (hrs)	
	m (g)	u%	m (g)	u%	m (g)	u%	m (g)	u%	m (g)	u%	m (g)	u%
1	2731	70%	1130	28%	1078	24%	1031	21%	999	18%	971	16%
2	2732	70%	1115	27%	1062	23%	1013	19%	980	16%	950	14%
3	2732	70%	1106	26%	1052	22%	1003	18%	970	16%	941	13%
4	2731	70%	1129	27%	1075	24%	1027	20%	994	18%	966	15%
5	2731	70%	1143	28%	1091	25%	1044	22%	1000	18%	968	15%
6	2730	70%	1160	29%	1111	26%	1066	23%	1025	20%	986	17%
7	2731	70%	1159	29%	1107	26%	1060	23%	1017	19%	978	16%
8	2731	70%	1144	28%	1092	25%	1045	22%	1019	20%	980	16%
9	2730	70%	1127	27%	1078	24%	1033	21%	1004	18%	992	17%
10	2731	70%	1088	25%	1037	21%	1009	19%	982	17%	964	15%
11	2732	70%	1063	23%	1014	19%	987	17%	965	15%	950	14%
12	2731	70%	1040	21%	996	18%	963	15%	946	13%	935	12%
13	2731	70%	1032	21%	985	17%	962	15%	944	13%	932	12%

The reduction in the number of trays in the middle has improved the moisture reduction uniformity. In this case, all of the trays have reached a lower 30% AMCOM in one day. The angle of the trays is changed to 6 degrees, and two air shields are added at the top of the first tray and the bottom of the last tray. All trays will reach the desired AMCOM within six days in this case.

Table 4. The AMCOM on each tray in second improved configuration (Case 3)

Hrs / Nº	0 (hr)		24 (hrs)		48 (hrs)		72 (hrs)		96 (hrs)		120 (hrs)	
	m (g)	u%	m (g)	u%	m (g)	u%	m (g)	u%	m (g)	u%	m (g)	u%
1	2731	70%	1134	25%	1076	21%	1024	17%	998	15%	985	14%
2	2731	70%	1162	27%	1102	23%	1048	19%	1020	17%	1007	16%
3	2730	70%	1170	27%	1109	23%	1054	19%	1026	17%	1013	16%
4	2731	70%	1198	29%	1134	25%	1077	21%	1051	19%	1025	17%
5	2729	70%	1223	29%	1166	26%	1113	22%	1072	19%	1046	17%
6	2731	70%	1230	29%	1172	26%	1119	22%	1078	19%	1051	17%
7	2732	70%	1231	30%	1172	26%	1120	23%	1075	19%	1049	17%
8	2731	70%	1224	29%	1166	26%	1113	22%	1072	19%	1046	17%
9	2731	70%	1214	29%	1157	26%	1105	22%	1064	19%	1038	17%
10	2731	70%	1127	28%	1067	24%	1014	20%	989	18%	966	16%
11	2731	70%	1078	27%	1022	23%	971	19%	946	17%	933	16%
12	2731	70%	1050	27%	996	23%	947	19%	922	17%	910	15%
13	2731	70%	985	26%	934	22%	888	18%	865	16%	854	15%

Table 5. Criteria calculated for three case

Case	u_a	S_u	S
1	-	-	-
2	14.8%	1.7%	11.7%
3	16.2%	1.1%	6.5%

The trays in the middle section need to increase the airflow exposure area by increasing the angle of the trays. The second improved configuration increases the angle of the 5th tray to the 10th tray to 12 degrees.

All the above experiments are conducted with approximately equal material weights on each tray. However, some trays always have better moisture reduction because they receive more air than the others, like those near the outlet and inlet, which can increase the material weight and therefore reduce the material in the other trays. The tray's weight is determined based on experience in previous experiments and the simulation result of the study by Nguyen Duc Trung et al. [8]. If more air flows through the trays, the weight of the material in the trays increases.

Table 6. AMCOM on each tray in the last case

Hrs / Nº	0 (hr)		24 (hrs)		48 (hrs)		72 (hrs)		96 (hrs)	
	m(g)	u%	m(g)	u%	m(g)	u%	m(g)	u%	m(g)	u%
1	2776	70%	1170	29%	1033	19%	1003	17%	988	16%
2	2720	70%	1149	29%	1035	20%	1006	17%	991	16%
3	2743	70%	1109	26%	1034	19%	1004	17%	989	16%
4	2716	70%	1122	27%	1079	23%	1012	18%	996	16%
5	2722	70%	1133	28%	1042	20%	1013	18%	998	17%
6	2713	70%	1076	24%	1039	20%	1009	17%	993	16%
7	2723	70%	1115	27%	1037	20%	1006	17%	991	16%

8	2731	70%	1084	24%	1032	19%	1003	17%	988	16%
9	2702	70%	1086	25%	1035	20%	1005	17%	990	16%
10	2737	70%	1105	26%	1030	19%	1001	17%	986	16%
11	2735	70%	1182	31%	1027	19%	1000	17%	984	15%
12	2740	70%	1091	25%	1036	20%	1009	17%	994	16%
13	2741	70%	1071	23%	1038	20%	1013	18%	998	17%

Table 7. Criteria calculated for last case

Case	u_a	S_u	S
4	16.0%	0.4%	2.3%

The drying time is minimal in all cases. The value of S_u and S is minimal, which shows the effectiveness of the last configuration. The trays angle values cannot be increased any further due to equipment limitations, so cases 3 and 4 approaches the optimal design of all the tested cases. Case 4 reaches the moisture content reduction homogeneity, and it can be concluded that the material weight in trays is direct with the amount of airflow the trays receive.

4. CONCLUSION

In this study, six experiments are conducted using different configurations in the chamber and a new method is used for determining the material weight on each tray. The results indicate that using a configuration with a middle trays angle of 12 degrees and the others of 6 degrees (13 trays in total) achieves greater product moisture homogeneity. It matches the prediction by CFD simulation in [8], where it has the most air uniformity. On the other hand, the material weight on the trays that have more air through the tray surface (shown in [8]) could be more than the others, which is the method for determining the material weight on each tray to obtain drying uniformity.

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