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Development of Moisture Adsorbing Mateial of Food Industry from Fermentation Residue – Distillery Grains

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Sorghum Distillery Residue Activated Carbons Paperboard (SDRACP), as the value–added materials of food industrial moisture adsorbing material, was developed from fermentation residue, namely distillery grains. The SDRAC was prepared from SDR and then made with the fiber material of wood pulp into the different proportions of SDRACP. The water activity (Aw) and hygroscopic ability of SDRACP were investigated. The percent weight with various Aw foods (AwF) with SDRACP at the relative humidity (RH) of 90 and 40% and temperature of 25℃ was evaluated. SDRACPs of Aw were 0.46–0.51, lower than the habitat for general microorganisms (0.60). The SDRACP for placing in high/middle/low AwF at 90% showed that the middle AwF were better than the others. For the SDRACP at low RH, the stability of the high AwF was better than that of the others. Moreover, the SDRACP with 40% of SDRACs added had a higher stability for the high/middle/low AwF than that for the other SDRACPs. The developed SDRACP can therefore be an optional food moisture adsorbing material for different Aw food systems in the food industry.

Key words: Sorghum Distillery Residue (SDR), Sorghum Distillery Residue Activated Carbons Paperboard (SDRACP), Water Activity (Aw), Water Activity Food (AwF), Moisture Adsorbing Material

INTRODUCTION

Sorghum distillery residue (SDR), a residual product brewed from sorghum liquor, belongs to fermentation wastes in the food industries. The annual output of SDR is about 135 600 MT and is within the top 20 in Taiwan in accordance with the statistics report for industrial waste (Environmental Protection Administration, 2016). The environmental protection problem has recently been proposed in Taiwan, especially for resource wastes, e.g. SDR; if they can be reused and/or regenerated, it can help the social and economic development. Research developments of SDR include: soil improvement and crop nutrition, compost materials, biotransformation using fungus, extracting antioxidants, functional application of extracts, production of ethanol biomass and feed improvement (Perdih *et al.*, 1991; Lee and Pan, 2003; Esperanza *et al.*, 2007; Bustamante *et al.*, 2007; Lafka *et al.*, 2007; Lin, 2008; Bustamante *et al.*, 2009; Dong *et al.*, 2010; Su *et al.*, 2010; Aliakbarian *et al.*, 2012; Anandan *et al.*, 2012; Nguyen Thi, 2012; Wang, 2012; Paradelo *et al.*, 2013). However, the growth of a microorganism, such as Escherichia coli, Salmonella or Staphylococcus aureaus, can produce aflatoxin, a toxic compound produced by a mold fungus in agricultural crops, if the SDR has not been carefully stored (Bustamante *et al.*, 2008).

The "Resource Recovery Program" and the "Full Waste Classification and Zero Waste Group Action Project" are promoted by the Environmental Protection Administration (EPA) in Taiwan. Activated carbon (AC) prepared from waste is part of their project; many studies have made related reports lately (Peng, 2006; Tseng *et al.*, 2007; Wu *et al.*, 2010; Lin *et al.*, 2015a; Lin *et al.*, 2015b). To promote the value–added and the wide application of fermentation wastes, including SDR in food industries, as well as to increase the demand for AC in Taiwan, it is important to find a means of resource reutilization for SDR that can be used as a precursor for preparing AC. Lin *et al.* (2015b) reported that the SDR can be prepared into AC with multiple mesopores, and used as functional water purifying material (Lin *et al.*, 2015c). The hollow structure and good absorption of AC can provide a functional adsorbent material, especially for a moisture adsorbing material for food use, such as placed in salt, pepper or flavoring jars to keep them dry and prevent deliquescence and foreign flavor, or as a treatment process, e.g. conserving medical drugs (Liou, 2012; Lin, *et al.*, 2014a; Lin, *et al.*, 2014b). Based on the distribution of pores in different diameters, pore structure and a high specific surface area, the specific surface area of AC, it is more applicable to adsorbing organic pollutants (Kienle and Bader, 1990). A trend related to the demand of AC has increased year–by–year in Taiwan, according to the import and export data from the Directorate General of Customs (2013). The average imported amount, especially over the last ten years, was about 16 889 tons of AC.

It is well known that safety should be considered when comparing the commercial moisture–proof material, silica gel and calcium oxide (CaO) because the appearance of silica gel is a transparent particle which can be eaten as crystal sugar, possibly resulting in uncomfortable pain; for CaO, it is white or gray–white with toxicity that, if eaten, results in an illness of the

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intestines and stomach (National Poison Center, 1990). On the other hand, food storage duration is significantly correlated to water activity (Aw). When food Aw is 0.0–1.0, it signifies high Aw foods (HAwF, >0.9), intermediate Aw foods (MAwF, 0.6–0.9), and low Aw foods (LAwF, <0.6). The minimum Aw for the growth of bacteria, yeast, fungi, halophilic bacteria, dryness enduring bacteria, and osmotic pressure enduring yeast are 0.90, 0.87, 0.80, 0.72, 0.62, and 0.60, respectively. As growth fails if Aw is lower than 0.60, high moisture and intermediate moisture foods need to be treated in special ways or mixed with preservatives and desiccant before preservation (Nicolau and Turtoi, 2006; Fontana, 2008).

The study prepared SDR into SDRAC made with the fiber material of wood pulp into the different proportions of SDRAC Paperboard (SDRACP), as the value–added materials of food industry–food moisture adsorbing material. Silica gel was used as the control group, and HAwF, MAwF and LAwF were placed in the environmental systems at the temperature of 25℃ with relative humidity of 90 and 40% to evaluate the Aw, and wt% of the foods. The feasibility of using SDRACP as a high efficiency moisture adsorbing material for different Aw food systems in various simulation environments was evaluated.

MATERIALS AND METHODS

Test materials

1. Sorghum distillery residue (SDR) as a precursor was obtained from K Liquor INC., Taiwan. The SDR was washed and had a moisture content of less than 15.0% after being air–dried at ambient temperatures.
2. Wood pulp: Nadelholz unbleached kraft pulps (NUKP) and Laubholz unbleached kraft pulps (LUKP) supplied by Cheng Loong Pulp, Taiwan.
3. Silica gel: procured by Feng Chang Co., Ltd., Taiwan
4. Water activity (Aw) foods: toast, cotton candy, and handmade biscuits as high, intermediate, and low Aw food (HAwF, MAwF, and LAwF) from Nabeisi Bread, Chiayi, Taiwan.

Experimental

Preparation of SDR activated carbon (SDRAC)

Referring to the method of Huang *et al*. (2010), Wu *et al*. (2010), Peng *et al*. (2012), Lin *et al*. (2014a) and Lin *et al*. (2015b) to prepare SDRAC, the precursor was dried in an oven at 105℃ for 24 h. For the first step–carbonization, the resulting specimen was loaded into a crucible, which was placed inside an upright high–temperature activation furnace (inner diameter, 26 cm; inner height, 40 cm) and was heated with a nitrogen (N_2 gas) flow rate of 200 mL /min for carbonization at a rate of 10℃/min. N_2 gas was added to make the container oxygen free. The carbonization temperature was set at 750, 800, and 850℃, successively. The second step, activation, inserted the activation gas–steam, which was heated from deionized water with a flow rate set at 90, 120 and 150 mL/h, respectively. The activation temperature was set at 800, and 850℃ with activation duration of 60 min. In the third step, it was cooled at N_2 gas flow rate 200 mL /min for 4 h, and removed at normal temperature to obtain SDRAC.

SDRAC Paperboard (SDRACP) –making method

Referring to the making method of Lin *et al*. (2015a), the basis weight of SDRACP was 360 g/m^2, and NUKP 20% and LUKP 80% were mixed using the beater method, mixed with 0, 10, 20, and 40% SDRACs by weight, made by a cylinder paper machine with the method of Beating Chinese National Standards (CNS) 12495 combined with the method of preparation of Handsheets CNS 11212. The SDRACP codes are SDRACP–activation temperature–flow rate– different proportions of SDRAC, such as SDRACP–800–120–S40 (SDRACP was made with SDRAC at 800℃ of activation temperature with the flow rate set at 120 mL/h and mixed 40% of SDRAC); the control group is PBO (without SDRAC; NUKP and LUKP only).

Determination of moisture content and Aw of SDRACP

The moisture contents (MC) of the various SDRACP specimens were determined according to the CNS3086 Method of Test for the Determination of Moisture Content in Pulp and Paper, and water activity (Aw) of SDRACP specimens was determined by placing 1 g of fine weighed specimen in accordance with CNS5225 Food Water Activity Determination.

Determination of MC and Aw of food

The MC in various foods was determined by referring to the test method of Lin *et al*. (2015a), while Aw was determined according to CNS5225 Food Water Activity Determination. The food Aw>0.9 is HAwF; the Aw 0.6–0.9 is MAwF; Aw <0.6 is LAwF (Nicolau and Turtoi, 2006; Fontana, 2008).

Hygroscopic ability of SDRACP

Referring to the test method of Lin *et al*. (2015a), about 1 g of air–dried BPO, and various SDRACP specimens were placed in the programmable constant temperature and humidity machine (TERCHYHRM, Taiwan), the hygroscopicity test was implemented at relative humidity (RH) 90 or 40% and the temperature of 25℃, the weights were measured at 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 6.0, 12.0, and 24.0 h, and measured once every 12 h, and then the percent weight was calculated till moisture equilibrium was reached. The computing equation is percent weight (%) = [(specimen weight − air–dried weight of specimen) / air–dried weight of specimen] × 100. The curves for the percent of absorption and desorption of the SDRACP specimen or silica gel were sketched.

Tests for SDRACP as moisture adsorbing material in food

This test used the different weight proportions of SDRAC made into SDRACP, applied to HAwF, MAwF, and

LAwF, and placed in 90 and 40% RH to simulate different Aw food systems. About 3.5 g PBO, various SDRACPs, and Silica gel of air–dried weight were placed in tightly sealed bags (ONY/PE) provided by Great & Power Top Co., Ltd., together with HAwF, MAwF, and LAwF, respectively, and then sealed by a capper. The HAwF, MAwF, and LAwF (without SDRACP) were used as the control groups, placed in the environmental systems at the temperature of 25℃ and 90 and 40% RH, respectively. The Aw of various SDRACPs and foods was tested. The percent weight for the adsorption and desorption results of various SDRACPs and foods at different RHs were evaluated. All specimens were tested once every 6 h till the test food became moldy according to visual observation. The formula of percent weight (%) = [(SDRACP or AwF weight − air–dried weight of SDRACP or AwF) / air–dried weight of SDRACP or AwF] × 100.

Statistical analysis

The test results were represented by a mean (standard deviation); the control group and test group were compared by Duncan's multiple range test (MRT). If the ρ value is smaller than 0.05, meaning a significant difference between the test group and the control group, it is represented by different superscript upper–case letters.

RESULTS AND DISCUSSION

MC and Aw of SDRACP

Table 1 shows the air–dried moisture content and Aw of various SDRACPs, Aw foods and Silica gel. The air–dried moisture content in the SDRACPs and PBO was 7.37–8.59%, that in Silica gel was 8.97%, and those of the toast, cotton candy, and handmade biscuits were 33.02, 18.77, and 4.47%, respectively. The Aw of Silica gel was 0.37, while that of SDRACPs and PBO was 0.46–0.52. Each microorganism has a limiting Aw, and microorganisms cannot grow, generate spores, or toxins if the Aw is lower than this limit value (Robertson, 2005; Powitz, 2007). The above results are lower than the Aw for the growth of all microorganisms (Chang *et al.*, 2006), and similar to (Lin *et al.*, 2014a; Lin *et al.*, 2015a). The Aw of toast, cotton candy, and biscuits were 0.95, 0.66, and 0.39, respectively, representing HAwF, MAwF, and LAwF, respectively (Gowen *et al.*, 2007; Fontana, 2008).

Hygroscopic ability of SDRACP

Figure 1 shows the hygroscopic ability of PBO, and various SDRACPs at 90 and 40% RH with the temperature of 25℃. At 90% RH, the percent weight of moisture absorption curve of various SDRACPs reached the peak at about 10 h, while the wt% increased by 4.41–7.46%; there was no significant difference among the various points from 10 to 96 h according to MRT. The moisture absorption curve became balanced after 10 h, and moisture absorption increased with SDRACPs. For 40% RH, the curve reached the valley and became balanced after about 18 h, and the wt% decreased by 1.69–5.07%; the higher the proportion of SDRACs, the more significant the moisture desorption.

The specimen Aw is identical to the ambient RH; the

Table 1. Air-dried moisture content and water activity of SDRACPs, Silica gel and different Aw foods

Specimen	Air-dried moisture content (%)	Aw [2]
BPO [1]	8.59±0.27 [5]	0.52±0.00
Silica gel	8.97±0.65	0.37±0.01
Toast	33.02±3.90	0.95±0.00
Candyfloss	18.77±0.15	0.66±0.00
Cookie	4.47±0.21	0.39±0.00
SDRACP-800-90-S10 [3]	8.08±0.11	0.49±0.00
SDRACP-800-90-S20	7.56±0.02	0.49±0.01
SDRACP-800-90-S40	7.43±0.21	0.50±0.01
SDRACP-800-120-S10	7.37±0.17	0.48±0.00
SDRACP-800-120-S20	8.12±0.11	0.51±0.01
SDRACP-800-120-S40	7.59±0.31	0.51±0.01
SDRACP-800-150-S10	8.03±0.23	0.48±0.00
SDRACP-800-150-S20	7.78±0.22	0.49±0.00
SDRACP-800-150-S40	7.45±0.08	0.50±0.00
SDRACP-S10 [4]	8.12±0.15	0.46±0.01
SDRACP-S20	8.43±0.45	0.48±0.01
SDRACP-S40	8.37±0.19	0.50±0.00

[1] PBO: the control group without SDRAC (Sorghum distillery residue activated carbon)
[2] Aw: Water activity
[3] SDRACP (SDRAC paperboard) – activation temperature – flow rate – different weight proportions of SDRAC
[4] SDRACP–S10: SDRACP–850–90–S10; S20 and S40: different weight proportions of SDRAC
[5] Mean ± standard deviation

specimen is without the moisture absorption and desorption phenomena, meaning the moisture absorption phenomenon occurs when the Aw is lower than the ambient RH; the moisture desorption phenomenon occurs when the Aw is higher than the ambient RH (Chang *et al.*, 2006; Lin *et al.*, 2015a). The proportion of SDRACs in the SDRACP contributes to its moisture absorption and desorption, where the higher the proportion, the better the moisture absorption and desorption, as the hysteresis loop is formed by the nitrogen adsorption/desorption isotherm of SDRAC. Lin *et al.* (2015b and 2015c) report that the nitrogen adsorption–desorption isotherms of the SDRAC were classified as Type IV, indicating the presence of microporous and mesoporous structures, according to the Bruauer, Deming, Deming and Teller (BDDT) Classification, and were H3 type hysteresis loops for most of the mesoporous structures in accordance with the International Union of Pure and Applied Chemistry. The SDRACPs can be regarded as a moisture adsorbing and desorbing material, which varies with ambient RH.

Aw variation of food treated with SDRACP

Table 2 shows the Aw change of SDRACPs, Silica gel and different AwF at 90% RH and 25℃ during different storage times. Aw decreased slightly with storage time for different SDRACP whatever the AW food was. The Aw stability of SDRACs for HawF and MawF was better than the other specimens, with variation about 0.02–0.03, followed by PBO and Silica gel, where the variation was about 0.03–0.04. The moisture in food can be divided into free water and bound water. The amount of free water is the level of Aw, which is regarded as one of important indices for inspecting food preservation (Maltini *et al.*, 2003; Sandulachi, 2012).

In the Aw test for SDRACPs in MAwF, the Aw increased with storage till the test food became moldy according to visual observation, as based on the deterioration or spoilage time. The Aw variation of MAwF was about 0.01–0.03. The SDRACP–S40 had the steadiest Aw, followed by PBO, Silica gel, and SDRACP–S10, where the Aw only increased by about 0.02 after 168 h. The Aw of SDRACP–S40 had insignificant difference from the initial time to about 378 h according to MRT. The Aw test for various SDRACPs in LAwF was also based on the deterioration of food surface (such as fungi); when the Aw variation was about 0.39–0.70, the SDRACP–S40, –S10 and Silica gel had better effect on the Aw of LAwF, and the variation was about 0.06 until 552 h. The Aw variation of Silica gel was from 0.39 to 0.66, followed by SDRACP–S40, from 0.39 to 0.69; however, PBO and AwF showed spoilage after 522 h.

The above results showed that the SDRACP–S40 has better Aw stability for HAwF, MAwF, and LAwF than the other specimens in 90 or 40% RH environments. The Aw variation of HAwF, MAwF, and LAwF resulted from the free water in the food and the free water in the environmental system becoming gradually balanced (Maltini *et al.*, 2003; Sandulachi, 2012), meaning that when the HAwF with Aw of 0.95 is placed at 90% RH, its Aw decreases gradually with time; whereas, the MAwF and LAwF with Aw of 0.66 and 0.39 increased gradually, till it balanced the ambient RH, resulting in the Aw variation (Lin *et al.*, 2015a).

If the Aw of food is controlled below 0.60, the microbial growth response can be decreased (Labuza *et al.*, 1970; Labuza, 1975; Torreggiani and Welti–Chanes, 1995). In addition to the Aw of food, the moisture absorption of SDRACP and a low RH environment can extend food storage time. MAwF and LAwF treated with SDRACP can be preserved longer than food treated

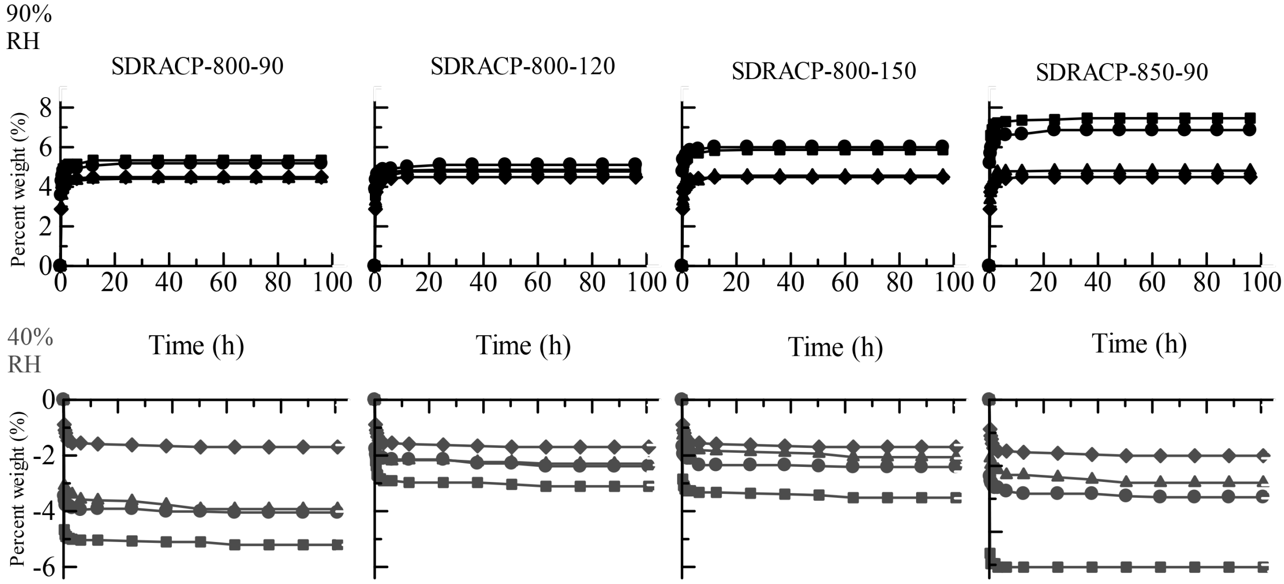

Fig. 1. Absorption and desorption change of SDRACP with different proportion of SDRAC at 90 and 40% RH with 25℃.

Legends ◆: PBO; ▲: SDRACP-S10; ●: SDRACP-S20; ■: SDRACP-S40
Note: Abbreviation is the same as Table 1

without SDRACP in a RH 90% environment. In the RH 40% environment, the Aw of HAwF and MAwF reached equilibrium with ambient RH, and Aw decreased gradually, meaning there is feasibility in prolonging storage life. As the level of Aw is significantly related to microbial growth and reproduction, decreasing the Aw of food contributes to prolonging storage life (Rockland and Stewart, 1981; Abdullah *et al.*, 2000; Barbosa–Cánovas *et al.*, 2008).

Percent weight of food treated with SDRACP

Effect of 90% RH on SDRACP and different Aw foods

Figure 2 shows the wt% of treating PBO, Silica gel, SDRACP–S10, and SDRACP–S40 in HAwF, MAwF, and LAwF, at RH 90% with 25℃. Figure 2 (a) indicates the wt% curve of SDRACP and Silica gel in HAwF, which increased from 0% (initial) to 10.87–11.54% (end), but there were no significant difference between SDRACP–S10 and –S40 in accordance with MRT. Figure 2 (b) shows the wt% curve of MAwF. The wt% of PBO, SDRACP–S10 and –S40 was about 1.66% after 378 h; Silica gel had the maximum moisture (8.28%). Figure 2 (c) shows that the wt% of the above three specimens was about 0.89% after 810 h, and Silica gel had the maximum moisture (10.02%) after 882 h. The PBO, SDRACP–S10 and –S40 were used in HAwF, MAwF, and LAwF at the end of the experimental period, and then the wt% became balanced. The wt% of SDRACPs in HAwF, MAwF, and LAwF systems after moisture adsorption were 10.87–11.54%, 0.00–1.66%, and 0.00–0.89%, respectively, where HAwF had the highest moisture adsorption, followed by MAwF, meaning the SDRACP regulated the moisture according to the food Aw. However, the wt% of Silica gel increased before the food deteriorated and spoiled at the end of experimental period for various AwF).

Figures 2 (d)–(f) show the wt% curves of HAwF, MAwF, and LAwF for treatment with SDRACPs and Silica gel. The wt% change of HAwF was –1.61 to –2.69% after 48 h, displaying the moisture desorption phenomenon (Fig. 2 (d)). This phenomenon may result from the food gradually reaching equilibrium with the ambient RH (Sahin and Sumnu, 2006); the Aw of toast (HAwF) is 0.95 (Table 1), and in the RH 90% environment the free moisture content may dissipate, thus decreasing the Aw. Figure 2 (e) shows that the wt% change of MAwF–PBO, MAwF–silica gel, MAwF, MAwF–SDRACP–S10 and S–40 was –0.27, –0.81, 0.01, and 0.00%. The MAwF–PBO and MAwF–Silica gel were in the state of moisture desorption; whereas, the MAwF only, MAwF–SDRACP–S10 and S–40 were in the moisture adsorption state. Figure 2 (f) shows the SDRACPs and PBO were between 3.67 and 3.94% after 882 h, which were greater than LAwF–Silica gel (3.03%);

Table 2. Water activity change of SDRACP, Silica gel and different AwF at 90% RH with 25℃ during different storage time

Food	Time (h)	PBO[1)] with various AwF	Silica gel with various AwF	Aw of AwF	SDRACP-S10 with various AwF	SDRACP-S40 with various AwF
HAwF	0	0.95±0.00 aD [2)]	0.95±0.00 aE	0.95±0.00 aE	0.95±0.00 aC	0.95±0.00 aD
	6	0.91±0.00 aA	0.93±0.00 bBCD	0.94±0.00 cD	0.93±0.00 cB	0.92±0.00 bA
	12	0.93±0.00 abC	0.93±0.00 abBCD	0.93±0.01 bC	0.92±0.00 aA	0.92±0.00 bA
	24	0.94±0.01 abC	0.93±0.01 aBC	0.94±0.01 abC	0.93±0.00 abB	0.92±0.00 aAB
	36	0.93±0.00 bC	0.93±0.00 bCD	0.93±0.00 bBC	0.93±0.00 bB	0.92±0.00 aB
	48	0.92±0.00 abA	0.91±0.00 aA	0.91±0.01 abA	0.92±0.01 bcAB	0.93±0.01 cCD
MAwF	0	0.66±0.00 aABC	0.66±0.00 aAB	0.66±0.00 aA	0.66±0.00 aA	0.66±0.00 aA
	6	0.66±0.01 aAB	0.67±0.00 bC	0.68±0.00 bB	0.67±0.00 abAB	0.66±0.00 aA
	24	0.65±0.01 aA	0.67±0.00 bC	0.68±0.00 cB	0.66±0.00 bA	0.67±0.00 bB
	96	0.66±0.01 aAB	0.67±0.00 bcC	0.68±0.00 cB	0.67±0.00 bcB	0.67±0.00 bBC
	168	0.67±0.00 bBC	0.67±0.00 bBC	0.68±0.00 cB	0.67±0.00 aB	0.67±0.00 aC
	330	0.69±0.00 dD	0.66±0.00 aAB	–	0.67±0.00 bB	0.66±0.00 aAB
	378	– [3)]	0.66±0.00 aA	–	0.68±0.00 bBC	0.67±0.00 aC
LAwF	0	0.39±0.00 aA	0.39±0.00 aA	0.39±0.00 aA	0.39±0.00 aA	0.39±0.00 aA
	6	0.40±0.00 aAB	0.39±0.00 aA	0.40±0.00 aAB	0.40±0.00 aA	0.40±0.00 aA
	24	0.41±0.00 bC	0.40±0.00 aB	0.43±0.00 cC	0.41±0.00 bB	0.41±0.00 bB
	168	0.46±0.00 cD	0.44±0.00 aC	0.50±0.00 dD	0.45±0.00 bC	0.44±0.00 aC
	522	0.62±0.00 dF	0.55±0.00 aF	0.70±0.00 eF	0.60±0.00 cE	0.59±0.00 bE
	810	–	0.66±0.00 aH	–	0.70±0.00 bG	0.69±0.00 bG
	882	–	0.68±0.01 aI	–	–	–

1) Abbreviation is the same as Table 1

2) Mean ± standard deviation; separation within lines by MRT at 5% significant level. The horizontal direction (AwF with different SDRACP and the others) is lowercase letters; the vertical (AwF with variation time) is uppercase letters

3) – : Food surface has occurred fungi (food became moldy)

LAwF–PBO had the largest increase, and with insignificant difference with SDRACP–S10 and –S40.

The wt% of HAwF, MAwF, and LAwF show that the SDRACP and Silica gel not only absorb the moisture in the environment, but also in the food. Gowen (2012) indicates that food storage life can be prolonged by decreasing the moisture in food. Their wt% became balanced when the PBO, SDRACP–S10 and –S40 were used in HAwF, MawF, and LawF till the end of experimental period. Moreover, the SDRACP is most suitable for MAwF, and the wt% is the steadiest, at about –0.01–0.00%. In other words, the storage environment also affects food, meaning when the ambient RH is high, food deteriorates quickly (Rockland and Stewart, 1981;

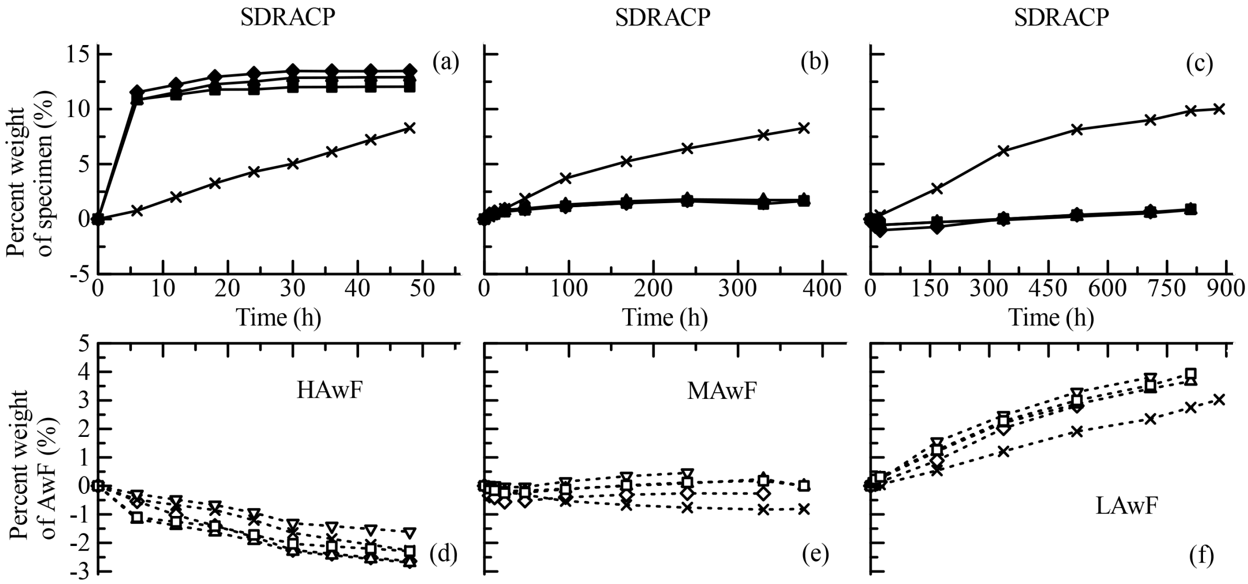

Fig. 2. Percent weight of SDRACP, Silica gel and HAwF, MAwF and LAwF in 90% RH at 25℃ during different storage time.

Legends —◆—: PBO; —✕— :Silica gel; —▲—: SDRACP-S10; —■—: SDRACP-S40
-◇-: AwF-PBO; -✕- : AwF-Silica gel; -▽- : AwF only;
-△-: AwF-S10; -□-: AwF-S40

Note: Abbreviation is the same as Table 1

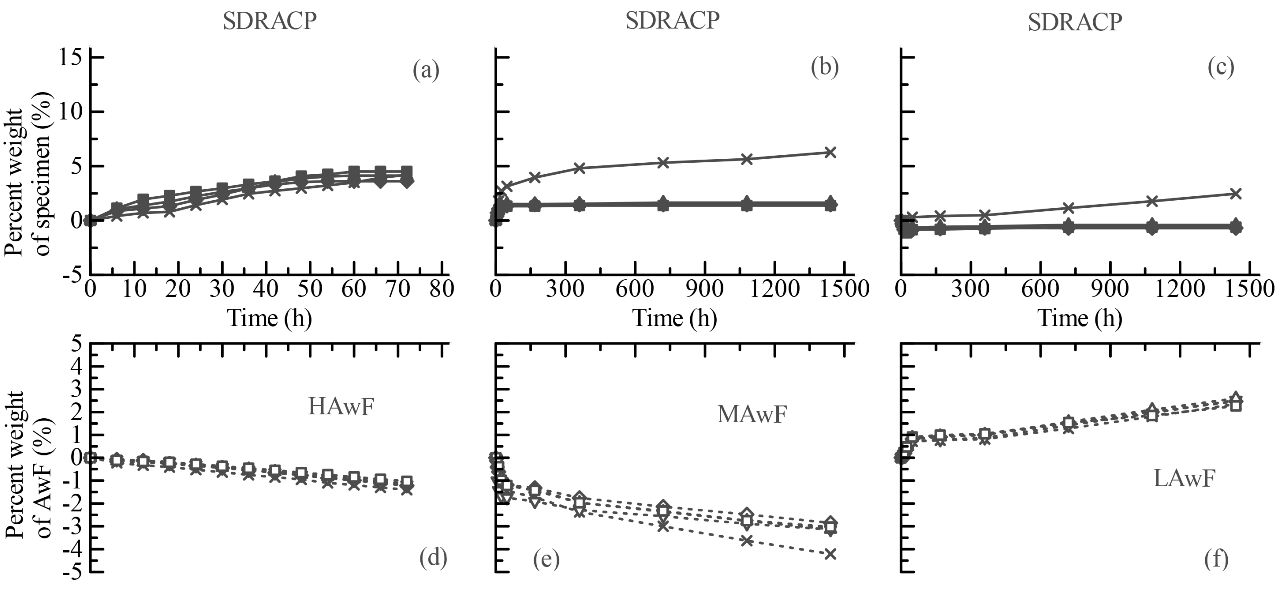

Fig. 3. Percent weight of SDRACP, Silica gel and HAwF, MAwF and LAwF in RH 40% at 25℃ during different storage time.

Legends —◆—: PBO; —✕— :Silica gel; —▲—: SDRACP-S10; —■—: SDRACP-S40
-◇-: AwF-PBO; -✕- : AwF-Silica gel; -▽- : AwF only;
-△-: AwF-S10; -□-: AwF-S40

Note: Abbreviation is the same as Table 1

Abdullah *et al*., 2000; Barbosa–Cánovas *et al*., 2008), such as spoilage.

Effect of 40% RH on SDRACP and different Aw foods

Figure 3 (a) shows the percent weight curves of SDRACPs and Silica gel applied to HAwF in the environment of RH 40% and 25℃. The result indicates an increase from 0% to 3.62–4.51%, where the SDRACP–S40 had the highest percent weight (4.51%), followed by Silica gel (4.13%), and the wt% curve of SDRACPs became gradually balanced after 50 h. Figure 3 (b) shows SDRACPs and Silica gel applied to MAwF, which was 1.38–6.27%, where the Silica gel had the highest wt%, the balance of SDRACPs occurred after 168 h, and the wt% was 1.33–1.35%. Figure 3 (c) shows LAwF; the wt% (–0.61 to –0.40%) of SDRACPs was balanced till 1440 h. Therefore, when PBO, SDRACP–S10 and SDRAC–S40 are used in various AwFs for a period of time, the wt% of food or SDRACPs becomes balanced. The wt% of HAwF, MAwF and LAwF were 3.62–4.51%, 1.38–1.65%, and –0.61 to –0.40, respectively. These results are the same as the trend in Figure 2. The SDRACP can reach moisture equilibrium in an environment of 90 or 40% RH; it then regulates the moisture according to the food Aw, while Silica gel cannot.

In the wt% curves of HAwF treated with the SDRACPs, the range of wt% was –1.03 to –1.40% after 72 h. (Fig. 4 (d)). For MAwF, it was from –4.21 to –2.85% (Fig. 4 (e)). Figures 3 (d) and 2 (e) show that the wt% of HAwF and MAwF have a negative tendency, representing the moisture desorption state, as the food gradually reaches equilibrium with ambient RH (Sahin and Sumnu, 2006). This concerns the original Aw of toast (HAwF) and cotton candy (MAwF), 0.95 and 0.66 (Table 1). Therefore, in the 40% RH environment, free moisture is desorbed and the Aw is decreased. Figure 3 (f) represents LAwF, where the wt% was 2.27–2.60%, and AwF with SDRACP–S10 had the maximum moisture absorption, 2.70%. Therefore, in an environment at 40% RH with 25℃, SDRACP was the most suitable for HAwF, –1.03 to – 1.40%, indicating that the variation of wt% is relatively stable.

CONCLUSIONS

The Aw of SDRACPs was 0.46–0.51, and the Aw of HAwF, MAwF, and LAwF were 0.95, 0.66, and 0.39, respectively. From the results of moisture adsorption and desorption abilities in the 90% RH, the hygroscopic ability of SDRACPs was increased; moreover, in the 40% RH, it was decreased. The moisture adsorption and desorption increased with the content of SDRAC in SDRACP. The food storage life of HAwF, MAwF, and LAwF with SDRACP at 40% RH was longer than that that at 90% RH; moreover, the SDRACP exhibited better results than the commercially available Silica gel. The HAwF, MAwF, and LAwF with SDRACP had the steadiest Aw. In other words, SDRACP not only absorbs the excess moisture in food as a food moisture adsorbing material, but also regulates the moisture with the ambient RH. In conclusion, SDRACP reaches moisture sorption equilibrium after a period of time, and regulates the moisture according to the foods' Aw, where the maximum moisture occurs in the HAwF, followed by MAwF. The SDRACP regulates the moisture with the ambient RH, meaning it is a variable moisture absorbing material for food in different RH environments.

AUTHOR CONTRIBUTIONS

Han Chien LIN designed this study, analyzed the data and the statistical analysis and wrote the paper. Rou–Jie CHU and Wen–Ju LEE performed the experiments and participated in the design of the study. Noboru FUJIMOTO supervised the work and provided resources. The authors assisted in editing of the manuscript and approved the final version.

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