Advance Journal of Food Science and Technology 8(3): 193-201, 2015
DOI:10.19026/ajfst.8.1491
ISSN: 2042-4868; e-ISSN: 2042-4876

Submitted: December 4, 2014 Accepted: January 8, 2015 Published: May 15, 2015

**Research Article**

# Modeling of Efficient Hot Air Drying of Apple Snails (*Pomacea canaliculata*) for Use as a Fishmeal Protein Substitute

[1]Du Luo, [1, 2]Haitao Zhang, [1]Xidong Mu, [1]Dangen Gu, [1]Meng Xu, [3]Jiaen Zhang, [1]Jianren Luo and [1]Yinchang Hu
[1]Institute of Pearl River Fisheries Research, Chinese Academy of Fishery Sciences, Key Laboratory of Tropical and Subtropical Fishery Resource Application and Cultivation, Ministry of Agriculture, Guangzhou 510380,
[2]College of Fisheries and Life Science, Shanghai Ocean University, Shanghai, 201306,
[3]Department of Ecology, College of Agriculture, South China Agricultural University, Key Laboratory of Ecological Agriculture, Guangzhou, 510642, China

**Abstract:** Snails are a kind of important aquatic products and dehydration is the main technique in production of snail meal. Apple snail (*Pomacea canaliculata*) dehydration meets both the demand for a fishmeal substitute in aquaculture and invasive species control in agriculture. In this study, we investigated the percentage of the nutritive material, examined the drying characteristics at 60, 80, 100 and 120°C, respectively, established a drying kinetics model and explored the effect of body morphology on drying efficiency. The results showed that the wet weight percentage of the soft parts was 46.61±6.18%. The drying efficiency was significantly improved with an increase of drying temperature from 60 to 120°C. The drying time increased rapidly when the final moisture content approached its equilibrium value. The Hii *et al*. model was selected as the best model to describe the drying curves ($R^2$>0.99). It provided a relatively accurate prediction between the requirements of moisture content and drying time. There were statistically significant differences ($p<0.01$) in the drying time at 10.0 and 1.0% moisture content level among the four temperature groups. The drying efficiency was significantly correlated to the mass of the soft parts. It was found that 100°C was an appropriate temperature to effectively dehydrate the fresh apple snails, whereas 60°C was not suitable when air velocity ≤0.5 m/s. This study explored an integrated approach to efficiently dehydrate snails for snail meal production, which will benefit both aquaculture and agriculture.

**Keywords:** Biological invasion, dehydration, golden apple snail, modeling, snail meal

## INTRODUCTION

Fish meal is a globally used feed ingredient supplement mainly in aquaculture (Shepherd and Jackson, 2013). The continued expansion of the aquaculture results in a global requirement to decrease production costs by substituting other materials for fishmeal (Tacchi *et al*., 2012). As one of the most seriously invasive mollusk pests, *Pomacea canaliculata* is widely distributed in more than 15 countries in the world (Joshi and Sebastian, 2006; Lv *et al*., 2011). A popular practice to control these pests is to use them as protein sources, as well as their use as biodiesel production catalysts (Viriya-Empikul *et al*., 2010) and environmental bioindicators (Koch *et al*., 2013). As a protein source in animal feed, the golden apple snail is widely used in the cultivation of pigs (Kaensombath, 2005), ducks (Teo, 2001), shrimps (Bombeo-Tuburan *et al*., 1995), turtles (Zhou and Qin, 2008) and fish (Da *et al*., 2012). Alternative use for this pest with an environmentally friendly technology would be a beneficial method of preventing damage (Serra, 1997). The golden apple snail has served as an important substitute protein source in fish meal, particularly in aquafeed, for two decades and this substitution could be more extensive given the expansion of these invasive snails globally and the increase of fish meal costs (Tacon and Metian, 2008).

In a previous study, we found that golden apple snails were nutritionally analogous to CP53.5% fishmeal, with a similar essential amino acid composition (Luo *et al*., 2012). They also have a similar proximate crude protein composition as fish meal (Jintasataporn *et al*., 2004). A proper level of snail meal supplementation will promote an optimum growth pattern for fish at a lower cost than with 100% fishmeal

**Corresponding Author:** Yinchang Hu, Institute of Pearl River Fisheries Research, Chinese Academy of Fishery Sciences, Key Laboratory of Tropical and Subtropical Fishery Resource Application and Cultivation, Ministry of Agriculture,1stXingyu Road, Liwan District, 510380 Guangzhou, P.R. China, Tel.: +86 20 81616088; Fax: +86 20 8616162

(Oyelese, 2007). As the key step in snail meal production, drying is a necessary process before the preservation and utilization of snails as food. Meanwhile, understanding the anatomical features and the dehydration characteristics of the snail are essential for the production of high quality snail meal and the control of production costs.

For golden apple snails, hot air drying is an inevitable cost effective method of drying that provides uniformity and minimizes contamination, environmental dependence and time (Doymaz, 2005). Both the samples and the drying conditions have tremendous consequences for drying efficiency (Sigge *et al*., 1998). Too long or short periods of drying might lead to poor quality for the final products (Horner, 1993). Variables such as temperature and air velocity, which can result in higher drying rates, are usually examined for the generation of economically and nutritionally acceptable final products (Agarry and Aworanti, 2012). Numerous mathematical equations have been used to describe the drying phenomena of various products. Among the frequently used models, thin layer drying models have found wide application due to their ease of use (Akpinar *et al*., 2003). Some commonly used models are the Page model, the Lewis model, the two term model and the Midilli *et al*. model, which are semi-theoretical models derived from the general solution of Fick's second law of diffusion (Murthy and Manohar, 2013). Empirical models derive a direct relationship between average moisture ratio and drying time. Depending on the experimental data, they describe drying curves for the conditions of the experiment and are easily applied to drying simulations (Hii *et al*., 2009).

Although the snails are widely used as supplemental protein sources, there is no report concerning snail meal production. Furthermore, there is no description about their dehydration characteristics to our knowledge. Therefore, the aim of the present study is:

- To examine the ratio of flesh to shell
- To observe the effect of temperature and body morphology on drying efficiency
- To construct a proper drying model to describe the drying kinetics
- To predict the drying time at each moisture content requirement using the selected model at different temperatures. In this study, we tried to optimize productivity, reduce production costs and customize snail meal to corresponding moisture content for safe storage or for special aquaculture use.

## MATERIALS AND METHODS

**Sample collection and pretreatment:** All golden apple snail (*P. canaliculata*) samples used in the experiment were randomly collected, using a selection standard of body mass >3 g, from the ditches of an aquaculture base (113°13′ 6″ E, 23°04′9″ N) in the Aquatic Invasive Risk Assessment Center, Pearl River Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou, China. Animals were divided into four groups and maintained in four aquariums (120 cm ×50 cm×50 cm) with air pumps at least 24 h after collection from the outdoor location. More than 30 individuals were used in each group and a total number of 148 animals (19.17±11.00 g) were examined.

**Main instruments:** During the experiment, the Electric Thermostat Blast Oven (DHG-9070A, Shanghai Yiheng Instruments Co., Ltd. Shanghai) was used as the dryer and the wind speed was simultaneously displayed by an anemometer (HT-8392, Guangzhou Hongcheng Electronic Technology Co., Ltd. and Guangzhou). The morphological features of the animals were measured using a vernier caliper (Tricle brand, 0-200, Shanghai Huiyi Measuring Instruments Co., Ltd., Shanghai). A digital analytical balance (AL204, Mettler Toledo (Shanghai) Co., Shanghai) was used to measure the mass of specimens.

**Drying procedure:** First, the mass of each snail was measured after wiping water from the snail's surface. Then, the shell was crushed using scissors, the sex was determined and the soft parts were transferred completely to a petri dish. The mass of the soft parts from each individual was detected before placing the material in the dryer, which was preheated to a preset temperature. Four temperatures (60°C (140°F), 80°C (176°F), 100°C (212°F) and 120°C (248°F)) were chosen for experiments and the mass change for a total number of 148 golden apple snails (*P. canaliculata*) with 37, 37, 42 and 32 individuals in each group, respectively, were evaluated using a digital analytical balance. In the 60 and 80°C groups, the weight changes were measured every 2 h, whereas in the 100 and 120°C groups, the changes were measured every hour. All samples were dehydrated with an air velocity of 0.52 m/s, as detected by an anemometer. When Moisture Content percentage ($MC_p$) could no longer be reduced at each temperature scale, the drying procedure was terminated.

**Data analysis and mathematical modeling:** The soft part weight percentage (SP) was calculated using the following formula:

$$SP = m_s/m_w \times 100\%$$

where,

$m_s$ = The mass of the soft part

$m_w$ = The whole mass of each golden apple snail including the shell

The moisture content percentage ($MC_p$) is calculated using the following formula:

Table 1: Selected drying models adapted for the drying of golden apple snails

| No. | Model name | Model equation | References |
|---|---|---|---|
| 1 | Lewis | $MR = -kt$ | Falade and Solademi (2010) |
| 2 | Wang and Smith | $MR = 1+at+bt^2$ | Wang and Singh (1978) |
| 3 | Newton | $MR = \exp(-kt)$ | Ayensu, (1997) |
| 4 | Henderson and Pabis | $MR = a\exp(-kt)$ | Akpinar *et al*. (2003) |
| 5 | Modified Henderson and Pabis | $MR = a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$ | Madhiyanon *et al*. (2009) |
| 6 | Logarithmic | $MR = a\exp(-kt)+b$ | Yaldiz *et al*.(2001) |
| 7 | Two term | $MR = a\exp(-kt)+b\exp(-gt)$ | Hii *et al*. (2009) |
| 8 | Two term exponential | $MR = a\exp(-kt)+(1-a)\exp(-a\cdot kt)$ | Yaldiz *et al*. (2001) |
| 9 | Diffusion approximation | $MR = a\exp(-kt)+(1-a)\exp(-b\cdot kt)$ | Akpinar *et al*. (2003) |
| 10 | Verma *et al*. | $MR = a\exp(-kt)+(1-a)\exp(-gt)$ | Verma *et al*. (1985) |
| 11 | Page | $MR = \exp(-kt^n)$ | Doymaz (2005) |
| 12 | Modified Page I | $MR = \exp[-(kt)^n]$ | Kavak Akpinar *et al*. (2006) |
| 13 | Modified Page II | $MR = \exp[(-kt)^n]$ | Wang *et al*. (2007) |
| 14 | Midilli *et al*. | $MR = a\exp(-kt^n)+bt$ | Midilli and Kucuk (2003) |
| 15 | Hii *et al*. | $MR = a\exp(-kt^n)+b\exp(-gt^n)$ | Hii *et al*. (2008) |
| 16 | Logistic | $MR = b/(1+a\exp(kt))$ | Jain and Pathare (2004) |

MR = Moisture ratio; *t* = drying time; *a*, *b*, *c*, *k*, *g* are constant parameters of the models

$$MC_p = \frac{\Delta m}{m_0} \times 100\% = \frac{m_0 - m_t}{m_0} \times 100\%$$

where,
$\Delta m$ = Mass change of the soft part
$m_0$ = The initial mass of the soft part
$m_t$ = The mass of the soft part at time t

The equilibrium mass of the soft part ($m_e$) is the mass detected at which the drying procedure no longer reduces the mass.

The Moisture Ratio (MR) was calculated using the following formula:

$$MR = \frac{X_t - X_e}{X_0 - X_e} = \frac{m_t - m_e}{m_0 - m_e}$$

where,
$X_0$ = The initial moisture content
$X_t$ = The moisture content at time t
$X_e$ = The equilibrium moisture content (Murthy and Manohar, 2013)

The Drying Rate (DR) during the procedure was calculated using the following equation:

$$DR = dx/dt = \frac{X_t - X_{t+dt}}{dt}$$

where,
dx = The change in moisture content
dt = The time elapsed during the drying process
$X_{t+dt}$ = The moisture content at time t+dt
$X_t$ = The moisture content at time t

For drying curve modeling, 16 drying models (Hii *et al*., 2008; Murthy and Manohar, 2013) based on other materials were used to select the best fit one mainly according to the correlation coefficient (Table 1).

The data are reported as the mean±Standard Deviation (SD). Microsoft Excel 2007 was used to record the data and for preliminarily analysis. SPSS 20.0 was used to analyze the data with the Independent Samples Test, Correlation Analysis and ANOVA.

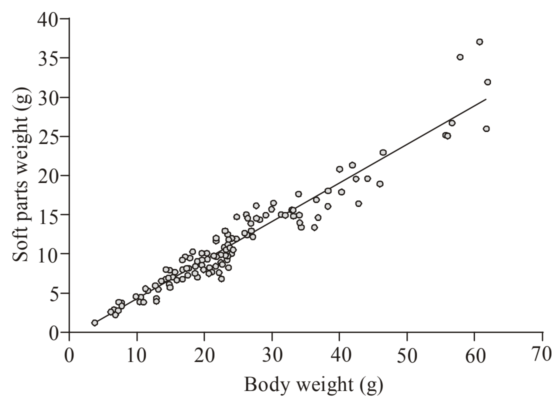


Fig. 1: Effect of body weight on soft part weight in golden apple snails

## RESULTS

**Ratio of flesh to shell:** The ratio of flesh to shell was expressed though the average soft parts weight percentage (SP). The total SP was 46.61±6.18% (n = 146). The effects of whole body weight ($m_w$) on soft parts weight ($m_s$) are displayed in Fig. 1. The $m_s$ increased linearly as $m_w$ increased. The SP regression line model is y = 0.4846x-0.39 ($R^2$ = 0.92), where y is the SP and x is $m_w$. However, there is nearly no correlation between $m_w$ and SP ($R^2$ = 0.0069). A relationship model was constructed to investigate if gender significantly affects SP. On one hand, the SP regression model of male snail is y = 0.4354x+0.7382 ($R^2$ = 0.83, n = 49). On the other hand, the SP regression model of female snail is y = 0.4944x-0.6572 ($R^2$ = 0.93, n = 96). Generally speaking, there was no significant difference between the weight percentage of the male (0.47±0.07, n = 49) and the female (0.46±0.06, n = 96).

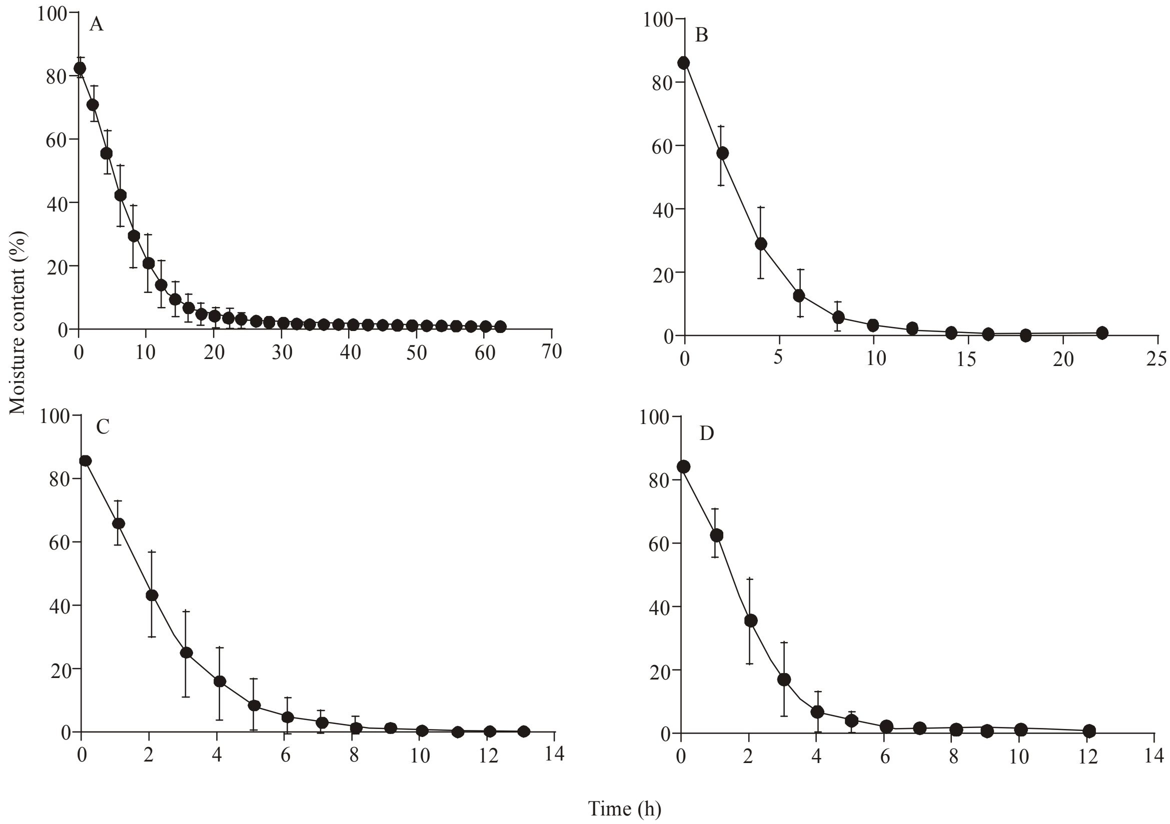


Fig. 2: Drying curves for the soft parts of the golden apple snail at different temperatures at a constant air velocity of 0.52 m/s; (a): Drying at 60°C; (b): Drying at 80°C; (c): Drying at 100°C; (d): Drying at 120°C

**Drying curves at various temperatures:** The change of moisture content percentage ($MC_p$) with the extension of drying time (t) was defined as the drying curves. The drying curves displayed the relationship between the relative dimensionless moisture content and the drying time. The MCp reduced with the increasing of drying time in each temperature scale (Fig. 2). The estimated initial moisture content percentages were 81.89±3.16% (n = 37), 84.59±2.66% (n = 37), 84.76 ±1.86% (n = 42) and 83.78±3.47% (n = 32) for the 60, 80, 100 and 120°C groups, respectively. The moisture content percentage 81.89±3.16% (n = 37) for the 60°C group was significantly smaller than the other three groups ($p<0.05$).

Overall, the drying curves of the four groups shared some variation trends and each of them could be divided into two parts by the point of $MC_p$= 10.0% (Fig. 2). The first part of the curve displayed a rapid decrease from the beginning, but the second declined slowly when the equilibrium moisture content was approached.

Correspondingly, the Drying Rate (DR) increased to a maximum in the first one or two hours and then decreased to zero with the decline of the moisture content to the balance point. It was worth noting that the drying efficiency became greater with an increase of the drying temperature from 60 to 120°C. In the middle of the drying procedure, the Standard Deviation (SD) of $MC_p$ had a greater variation of decreasing after an initial increase within a range of $MC_p$>5.0%.

**Mathematical modeling of drying kinetics:** When the dimensionless initial Moisture Ratio (MR) and the equilibrium moisture ratio were taken as 1 and 0, respectively, the models were used for regression of the experimental data, examining the Moisture Ratio (MR) against the drying time (t), according to the drying models presented in Table 1. After comparing the statistical parameters of various models, the Hii *et al*. (2008) model was selected as the best from the 16 models assessed to predict the drying characteristics of the soft tissue of golden apple snails undergoing hot air drying with an air velocity of 0.52 m/s at temperatures of 60 to 120°C according to the trends and estimated parameters. The Hii *et al*. model that best described the drying characteristic generated the highest $R^2$ and the lowest *RMSE* and additionally considered the Sum of Square Error (*SSE*), the Determination Coefficient (*DC*) and the empirical research. The estimated value of statistical and constant parameters for the Hii *et al*. model performed on the experimental data are presented in Table 2.

**Drying time estimation and model test:** The drying procedure is related to the evaporation and diffusion of

Table 2: The estimated values of parameters and constants of the Hii *et al*. model at various temperatures

| Temperature (°C) | *a* | *k* | *n* | *b* | *g* | $R^2$ | *RMSE* |
|---|---|---|---|---|---|---|---|
| 60 | 0.04565051 | 0.00540863 | 1.43077028 | 0.95174132 | 0.05555300 | 0.9999 | 0.0025 |
| 80 | 0.08788579 | 0.05182907 | 1.43330796 | 0.91199216 | 0.16137011 | 0.9999 | 0.0014 |
| 100 | 0.85178367 | 0.29529478 | 1.41704944 | 0.14805194 | 0.09137485 | 0.9998 | 0.0037 |
| 120 | 1.79111828 | 0.59333187 | 1.16785422 | -0.79138126 | 1.18756710 | 0.9997 | 0.0065 |

The model was $MR = a\exp(-kt^n) + b\exp(-gt^n)$. The letters *a*, *k*, *n*, *b* and *g* were constant parameters in the model; *R* is the Correlation Coefficient and *RMSE* is Root of Mean Square Error

Table 3: The partial drying time of the soft parts of golden apple snails by experiment and model estimation

| Temperature (°C) | DT1 (h) | EDT1 (h) | DT2 (h) | EDT2 (h) | DT3 (h) | EDT3 (h) |
|---|---|---|---|---|---|---|
| 60 (n = 32) | $14.5\pm3.7^A$ | 13.9 | $41.7\pm12.1^A$ | 46.6 | $57.4\pm12.3^A$ | 62.6 |
| 80 (n = 42) | $7.3\pm1.6^B$ | 6.7 | $13.7\pm3.3^B$ | 13.3 | $15.7\pm3.1^B$ | 15.9 |
| 100 (n = 37) | $5.0\pm1.5^C$ | 4.8 | $10.6\pm3.1^C$ | 10.5 | $13.1\pm4.4^{BC}$ | 12.4 |
| 120 (n = 37) | $3.7\pm1.0^D$ | 3.6 | $8.5\pm2.8^D$ | 6.2 | $10.6\pm3.4^C$ | 6.9 |

DT is the average experimental drying time, in which DT1 (MR<10.0%); DT2 (MR<1.0%) and DT3 (MR<0.5%) are compared to each other; EDT is the Hii *et al*. model's estimated drying time, in which EDT1 (MR<10.0%), DT2 (MR<1.0%), EDT3 (MR<0.5%) are predicted; The capital letters indicate the significant difference at 0.01 level and p values <0.01 are regarded as extremely significant

Table 4: Effects of the mass of soft parts and moisture content on drying time

| Groups | DT1 | Linear equations | DT2 | Linear equations | DT3 | Linear equations |
|---|---|---|---|---|---|---|
| ms60 | 0.86** | y = 0.446x+8.879 | 0.69** | y = 1.177x+26.887 | 0.69** | y = 1.191x+42.382 |
| MCp60 | -0.48** | | -0.58** | | -0.42* | |
| ms80 | 0.78** | y = 0.328x+4.217 | 0.62** | y = 0.548x+8.574 | 0.62** | y = 0.505x+10.92 |
| MCp80 | -0.61** | | -0.57** | | -0.60** | |
| ms100 | 0.85** | y = 0.262x +2.481 | 0.69** | y = 0.441x + 6.222 | 0.69** | y = 0.636x+6.845 |
| MCp100 | -0.44** | | -0.54** | | -0.41** | |
| ms120 | 0.81** | y = 0.127x+1.938 | 0.64** | y = 0.279x + 4.623 | 0.66** | y = 0.347x+5.697 |
| MCp120 | -0.64** | | -0.10 | | -0.08 | |

*: Means statistically significantly correlated and **: means highly significantly correlated. DT1, DT2 and DT3 stands for the drying time of samples with a moisture ratio (MCp) ≤10.0%, ≤1.0% and ≤0.5%, respectively; ms60, ms80, ms100 and ms120 denote the different masses of the soft parts in the 60, 80, 100 and 120°C, respectively groups; MCp60, MCp80, MCp100 and MCp120 denote for the moisture content percentage of the soft parts in the 60, 80, 100 and 120°C, respectively groups

water in the specimens. Accordingly, the moisture content was decreased as time elapsed increased at all temperature conditions and the minimum drying time was shortened with an increase of temperature from 60 to 120°C at all three moisture content levels of 10.0, 1.0 and 0.5%, respectively (Table 3). Table 3 shows the experimental and predicted drying time values under various drying temperature conditions. There are statistically significant differences (p<0.01) in the drying time at 10.0% moisture content level (DT1) and 1.0% moisture content level (DT2) of certain samples among the four temperature groups. There is no marked qualitative difference in the drying time at 0.5% moisture content level (DT3) between 80 and 100°C groups and between 100 and 120°C groups. However, the drying time for DT1, DT2 and DT3 at 60°C is much longer than the other groups.

The best suitable Hii *et al*. model was used to estimate the drying time to achieve a moisture content requirement of 10.0, 1.0 or 0.5%, respectively. Generally speaking, the model can be successfully used to calculate the drying time to reach a moisture content level of 10.0% (EDT1), 1.0% (EDT2) or 0.5% (EDT3) at four temperature scales. However, the model is better at estimating the drying time at 60, 80 and 100°C, respectively compared to the drying time at 120°C (Table 3). The prediction has the best fit with the experimental data in 80 and 100°C group at all three moisture levels. Nevertheless, comparing the estimated drying time with the actual experimental data, the assumed model gives a relatively more accurate prediction at 10.0% level at 100 to 120°C and 1.0 and 0.5% level at 60 to 80°C.

**Effects of body morphology on drying efficiency:** The effects of body morphology and body mass on drying efficiency were investigated. Collectively, the drying times DT2 and DT3 at each moisture content level were significantly correlated to DT1 with Pearson coefficients of 0.944 and 0.928, respectively. DT3 was correlated to DT2 with a Pearson coefficient of 0.966. This indicates that snail dehydration is a successive process. DT1, DT2 and DT3 were significantly correlated to the mass of the soft parts with Pearson coefficients of 0.383, 0.327 and 0.289, respectively. However, they were significantly negatively correlated to the initial moisture ratio with Pearson coefficients of -0.490, -0.490 and -0.439, respectively. The initial moisture ratio was significantly negatively correlated to the mass of the soft parts with a Pearson coefficient of -0.470 (n = 147, p<0.01, two tailed test).

Specifically, the drying time (MCp≤10.0%, MCp≤1.0% and MCp≤0.5%) was closely correlated to the mass of the soft parts with high coefficients in all four temperature groups (Fig. 3 and Table 4). The drying time increased with an increase of the body mass for both temperature and moisture content. Accordingly, there is an apparent linear relationship

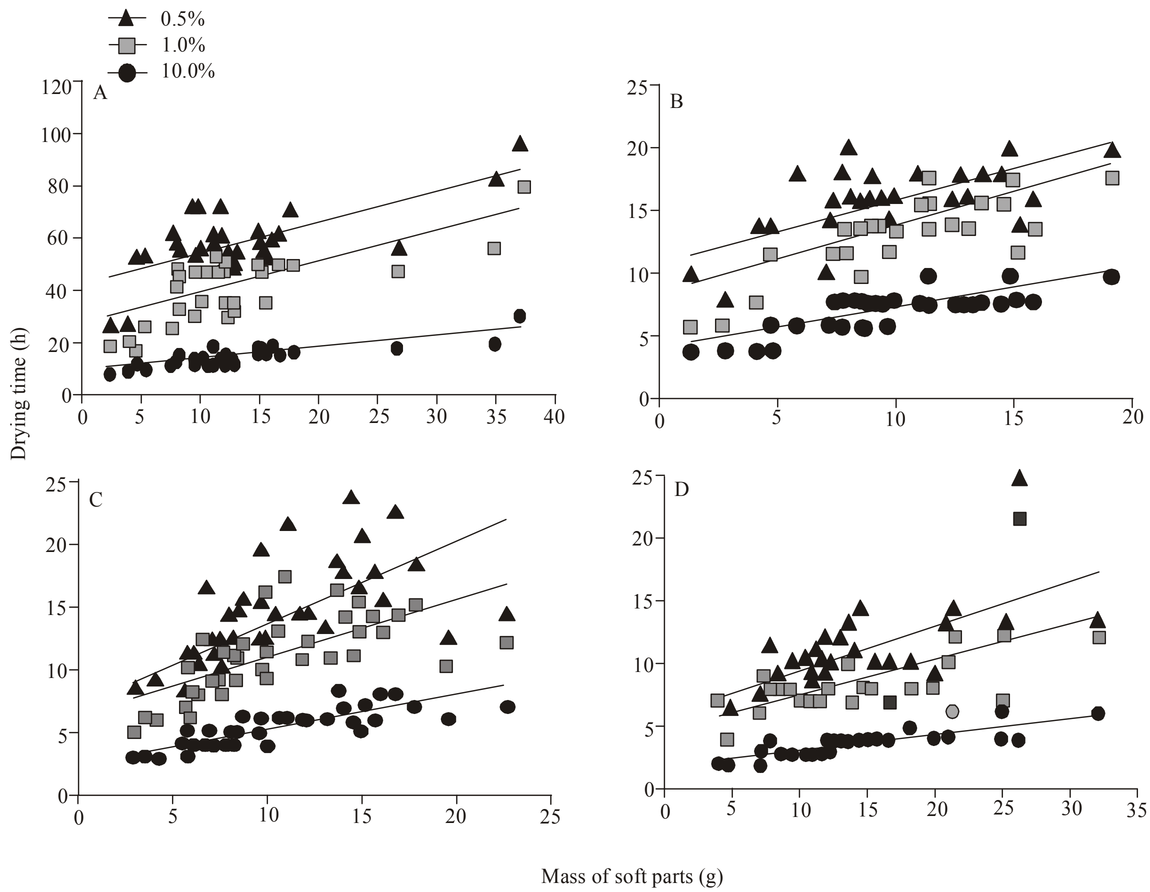


Fig. 3: Drying time is affected by the mass of the soft parts at various temperatures. The shortest experimental drying times were calculated when the moisture content (MCp) was ≤10.0%, ≤1.0%, ≤0.5%; (a): Drying at 60°C; (b): Drying at 80°C; (c): Drying at 100°C; (d): Drying at 120°C

between the body mass and the drying time at every MCp level for each temperature group. Furthermore, there is an obvious increase of the slope of the linear equations as the temperature decreases from 120 to 60°C. Similarly, the slope of the linear equations increased as the moisture content level decreased from 10.0 to 0.5% in each temperature group. Specifically, this enhancement was greater at the lower drying temperature of 60°C. The initial moisture content of the samples was somewhat significantly correlated to the drying time at every drying level except DT2 and DT3 at 120°C. However, there is no large difference in the correlation between the temperature groups at each drying level.

## DISCUSSION

Factors affecting the drying of food include the characteristics of the organisms (Kaale *et al*., 2013), the drying methods, the moisture requirement and the drying cost (Erbay and Icier, 2010). In the present study, we found that the hot air drying method was capable of dehydrating all of the soft tissue of golden apple snails efficiently at a low air velocity of approximately 0.5 m/s. The Hii *et al*. model used to describe the drying of cocoa beans described the drying kinetics well in all four temperature groups for golden apple snails (Hii *et al*., 2009). This suggests that the drying kinetics of animal products share some similarities with vegetable products. In the drying experiments, we observed that the samples could not be dehydrated as effectively at 60°C as at other temperatures if the moisture content decreased to less than 1.0%. Although 60°C dried the snails enough to meet the moisture requirements, it was at the expense of an obviously prolonged drying time. The drying efficiency improved as the temperature increased, but there was not a large significant difference between 100 and 120°C at a moisture content <0.5%. Because of giving off a faint fragrance, the snail meal dried at 100 and 120°C was the preferred food of mosquitofish (*Gambusia affinis*) compared to the other groups (D. Luo, unpublished data). Overall, these data suggest that 100°C is an appropriate choice for drying golden apple snails and the higher temperature of 120°C is time-saving and suitable for preliminary drying.

The successively declining moisture content and the significant correlation between different drying periods indicates that diffusion is the main mechanism governing moisture removal during hot air drying of snails. We supposed that the epidermis of the golden apple snails inhibits moisture evaporation, especially in the later drying period. That is why the heavier and larger the snails require a longer time to dry and is consistent with the inefficient drying rate at lower temperature, partially explaining the significantly lower final moisture content measurement at 60°C. The Fick's diffusion model has been used to describe the mechanism of moisture transfer during drying to determine the effective moisture diffusivity (Crank, 1975; Agarry and Aworanti, 2012). However, more work is needed to be done for the application of this model because of the visible shrinkage and morphological variations.

Thin layer drying refers to drying the sample as a single layer. Due to ease of use, thin layer drying models are widely applied to describe drying phenomena for various products. The Hii *et al*. model was developed by combining the advantages of the semi-theoretical Page and two-term models for thin layer drying, which have been found to fit the drying curves of various products (Hii *et al*., 2008).The close correlation of the model to the experimental data is consistent with the preliminary observation that the drying curves were divided into two terms. Because pretreatment would alter the effective moisture diffusivity (Agarry and Aworanti, 2012), the close mass-time correlation indicates that the morphology and mass extremely affected the drying rate and a preprocessing is essential for highly efficient snail meal production.

We made the crucial observation that the $MC_p$ was close to 50% and no significant difference was detected between the male and the female snails. However, more evidence is needed to certify the genetic control model of adult weight plasticity such as in the snail *Helix aspersa* (Ros *et al*., 2004) and if this feature is closely correlated to movements in the process of rapid invasive expansion. The weight of the edible soft parts for the golden apple snails is greater in comparison to bivalves (*Mytilus edulis*, *Geukensia demissa*, *Mercenaria mercenaria*) and other gastropods (*Littorina littorea*, *Nassarius obsoletus*, *Crepidula fornicata*) in wet weight (McKinney *et al*., 2004). On the other hand, more exploration concerning the utilization of the snail shell for other uses than biodiesel production catalysts and lead removers, which is close to 50% of the total weight, is greatly needed (Viriya-Empikul *et al*., 2010; Zhao *et al*., 2013).

Increases in the price of food globally would result in reduced consumption in lower income countries and in low-input industries (Green *et al*., 2013). The production of fishmeal has remained relatively constant. Continual expansion of aquaculture is resulting in a global requirement to reduce dependence on fishmeal and fish oil. An appropriate amount of fishmeal substitution would allow fish to grow with equal efficiency and with no significant difference in biometric quality parameters compared to those on a high marine protein diet (Tacchi *et al*., 2012). Aquaculture in East and Southeast Asia, the primary sites infested by the golden apple snail, consume the majority of fishmeal and fish oil. Molluscs are a protein resource for many aquatic animals (Liu *et al*., 2009). If there is an established snail meal production technique and golden apple snails are used as feed or a feed ingredient, the problem of snails infesting crops will be reduced and snails will increase in economic value and be viewed as an important resource to replace fishmeal (Bombeo-Tuburan *et al*., 1995).

## CONCLUSION

In conclusion, a constant proportion of 46.61±6.18% of the weight of the edible soft parts of the golden apple snail can be used to produce snail meal. Hot air drying efficiency is significantly affected by air temperature and body morphology. The Hii *et al*. model was selected as the most suitable model to describe the drying curves, which are two-termed and successively decreased with drying time. Drying temperature of 80, 100 and 120°C, respectively are more effective than 60°C. The most appropriate temperature to dry the soft parts of the golden apple snail is 100°C and a preprocessing step would greatly improve drying efficiency.

## ACKNOWLEDGMENT

This study was supported by funds obtained from the Natural Science Foundation of China-Guangdong Joint Funds (u1131006) and the Agricultural Biological Resources Protection and Utilization Project (2130108).

## REFERENCES

Agarry, S.E. and O.A. Aworanti, 2012. Modelling the drying characteristics of osmosised coconut strips at constant air temperature. J. Food Process Technol., 3: 151.

Akpinar, E.K., Y. Bicer and C. Yildiz, 2003. Thin layer drying of red pepper. J. Food Eng., 59: 99-104.

Ayensu, A., 1997. Dehydration of food crops using a solar dryer with convective heat flow. Sol. Energy, 59: 121-126.

Bombeo-Tuburan, I., S. Fukumoto and E.M. Rodriguez, 1995. Use of the golden apple snail, cassava and maize as feeds for the tiger shrimp, Penaeus monodon in ponds. Aquaculture, 131: 91-100.

Crank, J., 1975. The Mathematics of Diffusion: 2nd Edn., Clarendon Press, Oxford, UK.

Da, C.T., T. Lundh and J.E. Lindberg, 2012. Evaluation of local feed resources as alternatives to fish meal in terms of growth performance, feed utilisation and biological indices of striped catfish (*Pangasianodon hypophthalmus*) fingerlings. Aquaculture, 364-365: 150-156.

Doymaz, I., 2005. Drying characteristics and kinetics of okra. J. Food Eng., 69: 275-279.

Erbay, Z. and F. Icier, 2010. Thin-layer drying behaviours of olive leaves (*Olea europaea* L.) J. Food Process. Eng., 33: 287-308.

Falade, K.O. and O.J. Solademi, 2010. Modelling of air drying of fresh and blanched sweet potato slices. Int. J. Food Sci. Tech., 45: 278-288.

Green, R., L. Cornelsen, A.D. Dangour, R. Turner, B. Shankar, M. Mazzocchi and R.D. Smith, 2013. The effect of rising food prices on food consumption: systematic review with meta-regression. BMJ, 346: f3703.

Hii, C.L., C.L. Law and M. Cloke, 2008. Modelling of thin layer drying kinetics of cocoa beans during artificial and natural drying. J. Eng. Sci. Technol., 3: 1-10.

Hii, C.L., C.L. Law and M. Cloke, 2009. Modeling using a new thin layer drying model and product quality of cocoa. J. Food. Eng., 90: 191-198.

Horner, W.F.A., 1993. Drying: Chemical Changes. In: Macrae, R., R.K. Robinson and M.J. Sadler (Eds.), Encyclopaedia of Food Science, Food Technology and Nutrition. Academic Press, London.

Jain, D. and P.B. Pathare, 2004. Selection and evaluation of thin layer drying models for infrared radiative and convective drying of onion slices. Biosyst. Eng., 89: 289-296.

Jintasataporn, O., P. Tabthipwon and S. Yenmark, 2004. Substitution of golden apple snail meal for fishmeal in giant freshwater prawn, *Macrobrachium rosenbergii* (de Man) diets. Kasetsart J., 38: 66-71.

Joshi, R.C. and L.S. Sebastian, 2006. Global Advances in Ecology and Management of Golden Apple Snails. Philippine Rice Research Institute, Nueva Ecija, PH.

Kaale, L.D., T.M. Eikevik, K. Kolsaker and A.M. Stevik, 2013. Modeling and simulation of food products in superchilling technology. J. Aquat. Food Prod. T., 23: 409-420.

Kaensombath, L., 2005. Evaluation of the nutritive value of ensiled and fresh golden apple snails (*Pomacea spp*) for growing pigs. Ph.D. Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Kavak Akpinar, E., Y. Bicer and F. Cetinkaya, 2006. Modelling of thin layer drying of parsley leaves in a convective dryer and under open sun. J. Food Eng., 75: 308-315.

Koch, E., J.C. Altamirano, A. Covaci, N.B. Lana and N.F. Ciocco, 2013. Should apple snail *Pomacea canaliculata* (Caenogastropoda, Ampullariidae) be used as bioindicator for BDE-209? Environ. Sci. Pollut. Res. Int., 21: 761-765.

Liu, C., H. Zhou, Y. Su, Y. Li and J. Li, 2009. Chemical compositions and functional properties of protein isolated from by-product of triangle shell pearl mussel *Hyriopsis cumingii*. J. Aquat. Food Prod. T., 18: 193-208.

Luo, D., X.D. Mu, H.M. Song, D.E. Gu, Y.X. Yang, X.J. Wang, J.R. Luo, Y.C. Hu and J.E. Zhang, 2012. Nutritional components and utilization values of golden apple snails (*Pomacea canaliculata*) in different habitats. Chinese J. Ecol., 31: 2004-2010. (In Chinese with English Abstract)

Lv, S., Y. Zhang, P. Steinmann, G.J. Yang, K. Yang, X.N. Zhou and J. Utzinger, 2011. The emergence of angiostrongyliasis in the People's Republic of China: The interplay between invasive snails, climate change and transmission dynamics. Freshwater Biol., 56: 717-734.

Madhiyanon, T., A. Phila and S. Soponronnarit, 2009. Models of fluidized bed drying for thin-layer chopped coconut. Appl. Therm. Eng., 29: 2849-2854.

McKinney, R.A., S.M. Glatt and S.R. Williams, 2004. Allometric length-weight relationships for benthic prey of aquatic wildlife in coastal marine habitats. Wildlife Biol., 10: 241-249.

Midilli, A. and H. Kucuk, 2003. Mathematical modeling of thin layer drying of pistachio by using solar energy. Energ. Convers. Manage., 44: 1111-1122.

Murthy, T.P.K. and B. Manohar, 2013. Hot air drying characteristics of mango ginger: prediction of drying kinetics by mathematical modeling and artificial neural network. J. Food. Sci. Technol., 51(12): 3712-3721.

Oyelese, O.A., 2007. Utilization of processed snail meal and supplementation with conventional fishmeal in the diet of *Clarias gariepinus*. J. Fish Int., 2: 140-146.

Ros, M., D. Sorensen, R. Waagepetersen, M. Dupont-Nivet, M. SanCristobal, J.C. Bonnet and J. Mallard, 2004. Evidence for genetic control of adult weight plasticity in the snail *Helix aspersa*. Genetics, 168: 2089-2097.

Serra, A.B., 1997. The use of golden snail (*Pomacea sp.*) as animal feed. Tropicultura, 15: 40-43.

Shepherd, C.J. and A.J. Jackson, 2013. Global fishmeal and fish-oil supply: Inputs, outputs and markets. J. Fish Biol., 83: 1046-1066.

Sigge, G.O., C.F. Hansmann and E. Joubert, 1998. Effect of temperature and relative humidity on the drying rates and drying times of green bell peppers (*Capsicum annuum* L). Dry Technol., 16: 1703-1714.

Tacchi, L., C.J. Secombes, R. Bickerdike, M.A. Adler, C. Venegas, H. Takle and S.A. Martin, 2012. Transcriptomic and physiological responses to fishmeal substitution with plant proteins in formulated feed in farmed Atlantic salmon (*Salmo salar*). BMC Genomics, 13: 1-21.

Tacon, A.G.J. and M. Metian, 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. Aquaculture, 285: 146-158.

Teo, S.S., 2001. Evaluation of different duck varieties for the control of the golden apple snail (*Pomacea canaliculata*) in transplanted and direct seeded rice. Crop Prot., 20: 599-604.

Verma, L.R., R.A. Bucklin, J.B. Endan and F.T. Wratten, 1985. Effects of drying air parameters on rice drying models. T. ASABE, 28: 296-301.

Viriya-Empikul, N., P. Krasae, B. Puttasawat, B. Yoosuk, N. Chollacoop and K. Faungnawakij, 2010. Waste shells of mollusk and egg as biodiesel production catalysts. Bioresource Technol., 101: 3765-3767.

Wang, C.Y. and R.P. Singh, 1978. Use of variable equilibrium moisture content in modeling rice drying. T. ASAE, 11: 668-672.

Wang, Z., J. Sun, X. Liao, F. Chen, G. Zhao, J. Wu and X. Hu, 2007. Mathematical modeling on hot air drying of thin layer apple pomace. Food Res. Int., 40: 39-46.

Yaldiz, O., C. Ertekin and H.I. Uzun, 2001. Mathematical modeling of thin layer solar drying of sultana grapes. Energy, 26: 457-465.

Zhao, B.L., H. Peng, J.E. Zhang, X.Y. Dai and L. Peng, 2013. Lead removal from aqueous solution by the shell of golden apple snail and related mechanisms. Chinese J. Ecol., 32: 129-134. (In Chinese with English Abstract)

Zhou, W.G. and G.S. Qin, 2008. Effects on breeding mauremys mutica with different kinds of bait. Sichuan J. Zool., 27: 283-286. (In Chinese with English Abstract)