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Research Article
Physical Properties and Nutritive Values of Shell Meal Derived from Different Shellfish Species and Habitats

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Abstract

Background and Objective: The province of West Sumatra is rich in various species of shellfish that live in salt water and fresh water bodies, including the ocean, estuaries, lakes and rivers. This study aimed to evaluate the physical properties and nutritive values of shell meals produced from different shellfish species living in various habitats. **Materials and Methods:** Samples of shellfish were collected from 12 locations in 4 different water body types: Lakes, rivers, estuaries and oceans. Shell parts were separated, dried and weighed. The dried shells were then ground or subjected to open-air burning to produce 3 meal products: Raw coarse meal, raw fine meal and roasted meal. The products were weighed and analyzed for physical properties (bulk density, angle of response and particle size) and content of crude ash, Ca and P. The nutritive values of the meals were evaluated by mixing 3% shell meal with basal diet that was fed to 200 laying quails in a completely randomized design. There were four dietary treatments: Control diet (P0), basal diet+3% roasted meal (P1), 3% raw fine meal (P2) and 3% raw coarse particles (P3). The quail were divided into 20 experimental units of 10 birds each, so that each treatment consisted of 5 replications. Parameters measured include feed intake, egg production, feed conversion ratio (FCR) and egg shell quality. **Results:** The dried shells represented between 47 and 56% of the total body weight of the shellfish, with lake mussels having the highest percentage of shell parts ($p<0.05$). Raw coarse ground meal had the highest percentage of meal yield (98.7%), followed by raw fine meal (95.8%) and roasted meal (86.8%) ($p<0.01$). Raw coarse meals had higher bulk density and lower angle of response due to the higher percentage of large particles ($p<0.05$). The Ca content of roasted meal was significantly higher ($p<0.05$) than that of the raw meals. There was no significant effect of the different shell meal products on feed intake, egg production or FCR. However, quail fed a diet containing raw coarse ground shell (P3) had significantly better egg shell quality ($p<0.05$) than those fed the control diet (P0), P1 or P2. **Conclusion:** Shell meal that had coarse particles showed the best physical properties and nutritive values.

Key words: Fresh water shell, marine shell, shell meal, physical properties, nutritive values

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The province of West Sumatra is rich in bivalve shellfish living in various fresh water and terrestrial habitats of lakes, rivers, estuaries and the ocean. Mussels (*Corbicula* sp.) are abundant in three prominent lakes: Lake Maninjau (Agam district), lake Singkarak (Tanah Datar district) and lake Diatas (South Solok district) (Fig. 1). According to Zeswita *et al.*[1], two types of *Corbicula* are found in West Sumatra, *C. moltkiana*, which populate lake Maninjau and *C. sumatrana*, which are found in in lake Singkarak, Kembar lake and several rivers around the lake. Fresh water shellfish, referred to by the local name "pensi", are collected by fishermen mainly as a protein-rich food[1]. Shells represent about 41-50% of the total weight[2] of the shellfish and are usually either discarded or stacked at the lakeside to protect waterfront property[3].

Sea shells are also abundantly available in coastal regions. The province of West Sumatra is directly adjacent to the Indian Ocean and has about 375 km of shoreline[4]. There are five districts (South Pesisir, Agam, Pariaman, Padang Pariaman, Pasaman) and two cities (Padang and Pariaman) located along coastal areas in Indonesia (Fig. 1). In these regions, green mussel (*Perna viridis* L.) and blood clam (*Anadara antiquata* L.) are popular shellfish species that are collected as marine commodities by traditional small-scale fisheries. Green mussels, popularly known as 'kerang hijau' are found in estuaries, whereas, oysters referred to as 'kerang darah' inhabit brackish and salt water[5]. Edible portions of shellfish are sold for consumption[6], while 75-90% of shells from these shellfish are discarded[7]. The slow biodegradation of waste shells has raised concerns over disposal practices and environmental impact.

Fig. 1: Shellfish sampling sites in West Sumatra province, Indonesia
Source: https://ipfs.io/ipfs/QmXoypizjW3WknFiJnKLwHCnL72vedxjQkDDP1mXWo6uco/wiki/West_Sumatra.html

Given their abundance, waste shells could be used as local mineral feed ingredients for livestock. However, the Ca content of raw shell meal can vary by species and habitat, even though the shells typically contain at least 90% calcium carbonate ($CaCO_3$) by weight[8,9]. Furthermore, the shape, size and physical characteristics of shells also vary by species and habitat. Fresh water mussels generally have small, almost symmetrical, rounded to oval triangular-shaped shells[10], whereas, shellfish living in salt water and estuaries have a more pronounced shell symmetry and a slightly round or elongated shell shape. The crystal structures of oyster shells are largely aragonite and calcite, which have higher strengths and densities than other crystal types[11].

Shells in the form of raw coarse particle meal are often added to poultry feed as a calcium (Ca) supplement[12,13]. The mineral concentration of shell meal could be increased by burning raw shells prior to grinding to reduce organic matter. Burning of raw shells before grinding may also reduce crushing strength and produce a finer particle meal[14] that has a higher mineral concentration[15]. In this study, the amount of dried shell as a percentage of total body weight for four shellfish species living in different habitats was measured. The meal yield rate of processed dried shells was determined and the physical properties and mineral content of the meal products were analyzed. The nutritive values of shell meal products were evaluated in a feeding trial with laying quail.

MATERIALS AND METHODS

Sampling and processing of shellfish: Samples of four species of shellfish were collected in December, 2016 from 4 different water bodies: Lakes, rivers, estuaries and the ocean. The collected species were, lake mussel (*Corbicula moltkiana*), river mussel (*C. sumatrana*), green mussel (*Perna viridis* L.) and blood clam (*Anadara antiquata* L.). Samples were collected from local fishermen in three different locations for each water body, to yield 12 sampling sites that were distributed among seven districts in West Sumatra province, Indonesia (Table 1, Fig. 1).

At each sampling site, about 6 kg intact shellfish were washed thoroughly under running water to remove all dirt. The cleaned samples were then boiled to remove any residual tissues before drying under the sun for 5 days. To calculate the percentage of overall weight represented by the shell, the dried shell weight was divided by the total weight of the intact shellfish and multiplied by 10. The dried shells were divided into three parts with a ratio of about 1:1:2. The first and second parts were directly ground through 2.5 and 0.5 mm screen mills to produce raw coarse meal and raw fine meal, respectively. The third part was subjected to open-air burning prior to grinding to produce roasted meal. Each product containing coarse particles, fine particles and roasted meal was weighed to calculate the meal yield rate by dividing the weight of the meals by the total weight of the dried shells and multiplying by 100%.

Analysis of physical properties of shell meals: Representative samples of meal products were analyzed for physical properties (bulk density, compacted bulk density, angle of response and particle size) and dry matter (DM), crude ash, Ca and P content. Angle of response was measured using a cylinder placed on the bottom of a beaker according to a method described by Ogunsina *et al.*[16] with slight modifications. Briefly, the cylinder was filled from the top with shell meal. The cylinder was lifted gradually, allowing the material to flow out. The height (h) and diameter (d) (at base) of the resulting conical pile were measured and the angle of response (a) was expressed in degrees (°) calculated from the following formula: d = cotg (2 h/day). The angle of response indicates the degree of freedom that particles have to move in the stack and flow of the feed. Bulk density and compacted bulk density were measured using a 100 mm graduated cylinder according to a method described by Ruttloff[17]. Bulk density is the ratio of sample weight (w) to volume occupied by the sample (v) and was calculated as w/v in g mL^{-1}.

Table 1: Shellfish sampling sites in West Sumatra province, Indonesia

Shellfish type	Sampling site	Sub-district	District/city
Lake mussel	Lake Singkarak	Tanjung Mutiara	Tanah Datar
	Lake Maninjau	Tanjung Raya	Agam
	Lake Diatas	Lembah Gumanti	Solok
River mussel	Batang Agam	Payakumbuh Barat	Payakumbuh
	Sungai Durian	Lamposi Tigo Nagari	50 Kota
	Sungai Taram	Payakumbuh Barat	Payakumbuh
Green mussel	Tempurung gulf	Batang Kapas	Pesisir Selatan
	Jambak beach	Nan Sabaris	Padang Pariaman
	Carocok beach	Koto IX Tarusan	Pesisir Selatan
Blood clam	Air Manis beach	Padang Barat	Padang
	Tiram beach	Ulakan Tapakis	Padang Pariaman
	Bungus beach	Teluk Kabung	Padang

Table 2: Feed components, crude nutrient composition and energy concentration of experimental diets

		Basal diets supplemented with lake mussel shell meal		
	Control P0	Roasted meal P1	Raw fine meal P2	Raw coarse meal P3
Feed component (%)				
Yellow corn	44.00	45.00	45.00	45.00
Layer concentrate 126	42.00	44.00	44.00	44.00
Rice bran	6.50	2.50	2.50	2.50
Coconut oil	2.00	2.00	2.00	2.00
Premix[1]	1.00	1.00	1.00	1.00
Salt	0.50	0.50	0.50	0.50
Limestone meal	2.00	-	-	-
Bone meal	2.00	2.00	2.00	2.00
Roasted shell meal	-	3.00	-	-
Raw fine shell meal	-	-	3.00	-
Raw coarse shell meal	-	-	-	3.00
Total	100.00	100.00	100.00	100.00
Calculated nutrient and energy compositions				
Crude protein (%)	18.22	17.70	18.70	18.70
Crude fiber (%)	3.51	3.51	3.51	3.51
Crude fat (%)	6.18	6.18	6.18	6.18
Ca (%)	3.02	3.02	3.02	3.02
P (%)	0.78	0.78	0.78	0.78
ME (kcal/kg)	2,761.52	2,761.52	2,761.52	2,761.52

[1]Supplied per kilogram of diet: Vitamin A: 10,000 IU, Cholecalciferol: 2,000 IU, Vitamin E: 10 mg, Vitamin K3: 2 mg, Thiamine: 1 mg, Riboflavin: 5 mg, Pyridoxine: 2 mg, Vitamin B12: 0.0154 mg, Niacin: 125 mg, Calcium pantothenate: 10 mg, Folic acid: 0.25 mg, Biotin: 0.02 mg, BHT: 30 mg, Selenium: 0.1 mg, Iron: 40 mg, Copper: 12 mg, Zinc: 120 mg, Manganese: 100 mg, Iodine: 2.5 mg, Cobalt: 0.75 mg

Particle size was determined by sieve analysis using a Retsch VS 1000 sieve shaker (Retch GmbH, Germany). Samples (~300 g) were at first oven-dried for 24 h. The dried samples were then sieved for 10 min using a set of sieves with 0.02-0.76 mm mesh. The particles retained by each sieve were weighed and the percentage of each particle size was then calculated as the weight of the retained particles divided by the total weight of dried sample and multiplied by 10. Cumulative percentages of particle size were calculated from the sum of sample percentages retained by the sieves.

Analysis of crude ash and mineral content of shell meal: Coarse meals were finely ground through a 1 mm screen mill prior to analysis of crude ash, DM and mineral (Ca, P) content using proximate analysis procedures described by the Association of Analytical Communities[18]. Samples for mineral analysis were prepared by wet digestion with concentrated sulfuric acid and hydrogen peroxide. The concentration of minerals was determined by atomic absorption spectrophotometry[19]. All results were reported on a DM basis.

Feeding trial: The nutritive values of lake mussel shell meal, which had values that were closest to the average values for physical properties and nutrient content of all shell meals tested, were evaluated by mixing 3% shell meal with basal diet that was fed to 200 laying quails (aged 8 weeks, average body weight 127.6±10.44 g/bird) for 6 weeks. The quail were divided into 20 experimental units (10 birds each) such that each treatment consisted of 5 replications. There were four dietary treatments: Control diet (P0), basal diet+3% coarse particles (P1), 3% fine particles (P2) and 3% roasted meal (P3). Control (P0) was basal diet supplemented with 2% of limestone meal.

Basal diets were prepared using 45, 44 and 2.5% commercial layer concentrate, corn and rice bran, respectively. All diets were formulated to be iso-nitrogenous and iso-caloric (Table 2). The nutrient and energy compositions calculated based on chemical analysis of feed components were normalized relative to the standard requirements of laying quail during the production period recommended by the NRC[20]. The following performance parameters were evaluated: Feed intake, egg production, feed conversion ratio (FCR), egg weight and egg shell quality.

Statistical analysis: Data on the percentage of dried shell were subjected to one-way analysis of variance using a completely random 4×3 design, consisting of 4 water bodies and 3 sampling sites, whereas, data for meal yield rates, physical properties and particle size distribution were analyzed in a completely factorial design of 4×3×3 with 4 water bodies, 3 different meal products and 3 sampling sites as replications. Feeding trial data were analyzed in a completely randomized design with 4 diet treatments and 5 groups of laying quails as replicates. Standard deviations and 95% levels of confidence were also evaluated. Duncan's multiple range test (DMRT) was applied to separate means. Differences were considered significant at $p<0.05$[21].

RESULTS

Dried shell and meal yield rates: Shellfish obtained from the various sampling sites showed different visual characteristics, especially between shellfish that live in fresh water and in the ocean (Table 3). Fresh water mussels generally have a small, dark, almost symmetrical, rounded to oval triangular shells, whereas, shellfish living in salt water and estuaries have a larger, thicker and stronger shell that is slightly round or elongated. The dried shells represented between 47 and 56% of the total body weight (Table 3). Lake mussels had the highest shell weight (56.3%), which differed significantly from green mussel (51.7%), river mussel (50.2%) and blood clam (47.7%), that all had similar percentages of shell weight. Raw coarse ground meals had the highest percentage yield (98.7%), followed by raw fine meal (95.8%) and roasted meal (86.8%) ($p<0.01$). Roasted shell meals produced from lake mussel (83.7%) had the lowest meal yield, followed by river mussel (83.6%). The blood clam had the highest roasted meal yield at 91.0%, followed by the green mussel at 88.8% (Table 3).

Physical properties and particle size of shell meals: The bulk density and angle of response among the different meals ranged from 1.13-1.52 g mL^{-1} and 43.83°-56.11°, respectively (Table 4). Raw coarse meal had the highest bulk density and lowest angle of response, followed by raw fine meal and roasted meal. Raw coarse meals produced from green mussel and sea oyster shell had higher bulk density and angle of response than that produced from fresh water mussels. Blood clam shells had the highest bulk density values, whereas, mussel shells from different habitats had similar bulk densities. Roasted meal showed the highest angle of response, followed by raw fine meal and raw coarse meal. There was no statistically significant effect of shellfish species and living habitat on bulk density, angle of response and particle size of roasted meal.

Raw coarse and fine particle products contained significantly higher amounts of coarse and medium particles than the roasted meals (Table 4, Fig. 2). Bulk density was positively correlated with larger particle size. In contrast, decreased particle size increased the angle of response. Blood clam shell meal had the highest percentage of fine particles, but the lowest large and medium particle size relative to products from other mussel shells. In roasted meal, fine particles dominated (75-80%), whereas, only 5-6% was coarse particles (Table 4, Fig. 2).

Table 3: Percentage of dry shells and shell meal products

	Living habitat				
	Lakes	Rivers	Estuaries	Marine	Mean
Intact shellfish					
Shell parts					
Common name	Lake mussel	River mussel	Green mussel	Blood clam	
Local name	Pensi Danau	Pensi Sungai	Kerang Hijau	Kerang Darah	
Latin name	*Corbicula moltkiana*	*Corbicula sumatrana*	*Perna viridis*	*Anadara antiquata* L.	
Percentage of dried shell (%)	56.34±0.83[a]	50.25±2.43[b]	51.66±0.71[AB]	47.73±0.23[c]	51.91±3.62
Rate of meal yield (%)					
Raw coarse meal	98.72±0.20[a]	99.36±0.21[a]	97.42±0.74[b]	99.08±0.64[a]	98.65±0.24[A]
Raw fine meal	96.38±0.18[cd]	94.13±2.07[e]	96.96±2.00[bc]	95.64±0.90[d]	95.78±0.79[B]
Roasted meal	83.73±1.55[h]	83.63±2.36[h]	88.82±1.73[g]	90.96±2.34[f]	86.79±0.36[C]
Mean	92.95±0.53[c]	92.37±0.62[c]	94.40±1.35[b]	95.23±0.77[a]	

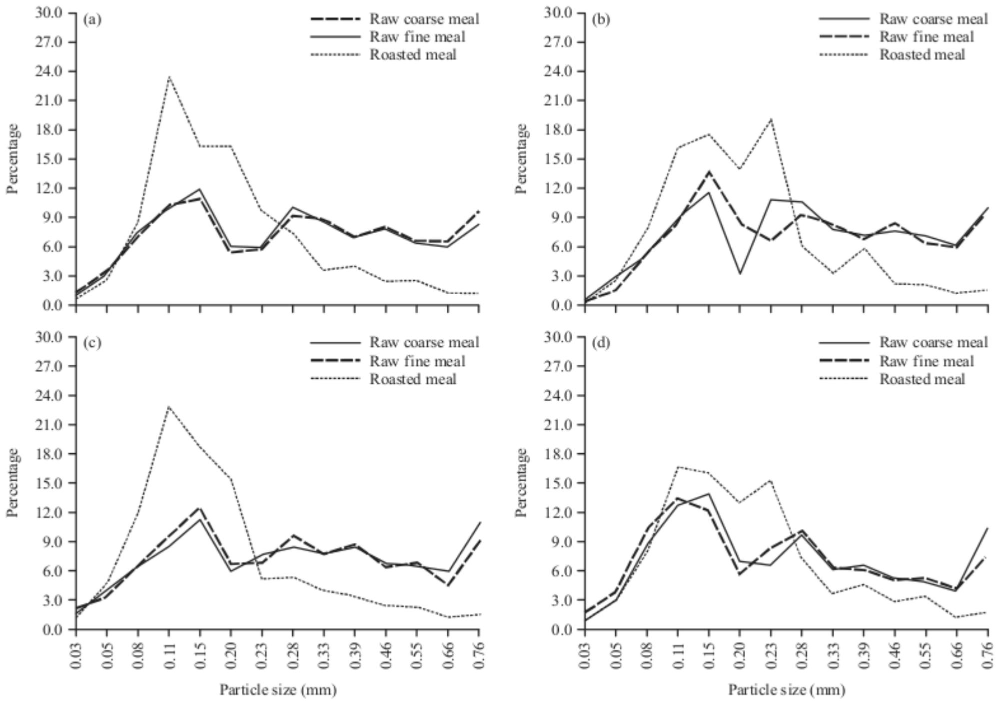

Fig. 2(a-d): Particle size distribution of shell meals derived from different habitats and processing method, (a) Lake mussel, (b) Green mussel, (c) River mussel and (d) Blood clam

Table 4: Physical properties and particle size distribution of shell meals

	Shell type				
Parameters	Lake mussel	River mussel	Green mussel	Blood clam	Mean
Bulk density (g mL^{-1})					
Raw coarse meal	1.47±0.02^{b}	1.47±0.02^{b}	1.52±0.04^{a}	1.46±0.02^{b}	1.48±0.02^{A}
Raw fine meal	1.41±0.02^{c}	1.43±0.03^{c}	1.41±0.02^{c}	1.39±0.04^{cd}	1.41±0.03^{B}
Roasted meal	1.16±0.0^{e}	1.20±0.03^{e}	1.13±0.04^{e}	1.37±0.07^{d}	1.22±0.03^{C}
Mean	1.35±0.01^{b}	1.37±0.01^{b}	1.35±0.06^{b}	1.41±0.03^{a}	
Angle of response (°)					
Raw coarse meal	43.83±2.33^{d}	44.96±1.47^{d}	46.36±0,96^{c}	47.69±0,46^{c}	45.71±1.30^{C}
Raw fine meal	50.58±2.50^{b}	47.67±1.21^{c}	51.27±0.96^{b}	50.99±0,39^{b}	50.13±1.13^{B}
Roasted meal	55.06±0.88^{a}	55.45±1.74^{a}	55.97±0.54^{a}	56.11±1.87^{a}	55.65±1.26^{A}
Mean	49.82±1.44^{BC}	49.36±0.46^{c}	51.20±0.10^{AB}	51.60±0.78^{a}	
Fine particles ($\leq$0.25 mm) (%)					
Raw coarse meal	44.28±3.42^{c}	45.53±0.20^{c}	43.56±1.33^{c}	52.93±1.08^{b}	46.58±4.31^{C}
Raw fine meal	45.80±2.84^{c}	47.47±3.45^{c}	44.77±1.69^{c}	55.31±1.95^{b}	48.34±4.78^{B}
Roasted meal	77.62±1.66^{a}	79.98±5.55^{a}	77.43±3,05^{a}	75.01±8.17^{a}	77.51±2.03^{A}
Mean	55.90±18.83	57.66±19.35	55.25±19.21	61.09±12.12	
Medium particles (0.25<x$\leq$0.50 mm) (%)					
Raw coarse meal	33.11±0.53^{a}	31.21±1.11^{a}	33.31±1.21^{a}	27.84±2.24^{b}	31.63±2.68^{A}
Raw fine meal	33.53±0.66^{a}	32.30±1.11^{a}	33.01±3.31^{a}	27.69±2.91^{b}	30.72±2.89^{A}
Roasted meal	17.39±1.42^{c}	15.02±3.78^{c}	17.54±2.44^{c}	18.55±4.97^{c}	17.12±1.50^{B}
Mean	28.01±9.2	26.18±9.68	27.53±8.66	24.69±5.32	
Coarse particles (>0.50 mm) (%)					
Raw coarse meal	22.61±3.20^{a}	23.26±1.11^{a}	23.13±1.98^{a}	19.23±3.25^{b}	22.24±2.07^{A}
Raw fine meal	20.67±2.89^{b}	20.23±4.22^{b}	22.23±2.01^{a}	16.99±2.47^{c}	20.03±2.20^{B}
Roasted meal	4.99±0.35^{d}	5.01±1.83^{d}	5.03±0.99^{d}	6.44±3.33^{d}	5.30±0.92^{C}
Mean	16.09±9.66	16.17±9.78	17.03±10.42	14.22±6.83	

Table 5: Crude ash, mineral and dry matter content of shell meals

	Shell type				
Nutrients/products	Lake mussel	River mussel	Green mussel	Blood clam	Mean
Crude ash (% DM)					
Raw shell meal	86.7±1.72	83.58±1.68	83.21±2.59	81.07±4.18	83.64±2.32
Roasted meal	79.98±3.72	82.81±7.79	84.69±0.95	87.29±5.56	83.69±3.08
Mean	83.34±2.72	83.19±4.19	83.95±1.05	84.18±4.74	
Ca (% DM)					
Raw shell meal	34.39±1.95^{b}	31.35±2.71^{c}	35.83±1.36^{a}	34.98±0.86^{AB}	34.14±1.95^{B}
Roasted meal	35.10±1.17^{a}	34.88±1.33^{AB}	36.04±1.57^{a}	36.35±0.19^{a}	35.77±0.63^{A}
Mean	34.75±0.67^{a}	33.11±1.58^{b}	35.93±1.12^{a}	35.66±0.51^{a}	
P (% DM)					
Raw shell meal	0.40±0.06	0.32±0.10	0.32±0.04	0.38±0.05	0.36±0.04
Roasted meal	0.32±0.14	0.31±0.10	0.36±0.06	0.39±0.02	0.34±0.04
Mean	0.36±0.08	0.31±0.06	0.34±0.02	0.39±0.03	
Dry matter (DM) (%)					
Raw shell meal	98.46±0.54	98.13±0,17	97.91±0.84	97.88±0.62	98.09±0.26
Roasted meal	98.07±0.49	98.53±0,66	98.69±0.03	98.49±0.49	98.44±0.27
Mean	98.27±0.07	98.32±0.43	98.30±0.43	98.18±0.55	

Table 6: Feeding trial results: Feed intake, egg production, feed conversion ratio (FCR) and egg shell quality of quail

	Basal diets supplemented with shell meal			
Parameters	Control P0	Roasted meal P1	Raw fine meal P2	Raw coarse meal P3
Feed intake (g/bird/day)	24.71±1.39	24.50±1.06	25.43±0.85	25.37±1.46
Egg production				
Egg number (egg/bird)	28.64±1.52	29.54±1.41	29.10±1.96	31.22±4.53
Egg mass (g/bird)	300.23±13.75	310.16±17.29	310.19±23.99	334.16±47.91
Quail-day egg production (%)	69.19±3.61	70.33±3.36	69.29±4.66	74.33±10.79
FCR	3.36±0.05	3.33±0.16	3.46±0.16	3.23±0.31
Egg shell quality				
Egg weight (g/egg)	10.33±0.14	10.35±0.14	10.52±0.31	10.50±0.17
Egg shell weight (g/egg)	0.83±0.03^{c}	0.89±0.03^{b}	0.89±0.19^{b}	0.93±0.16^{a}
Percentage of egg shell (%)	8.02±0.20^{c}	8.39±0.29^{b}	8.36±0.21^{b}	8.78±0.16^{a}
Egg shell thickness (mm)	0.182±0.00^{d}	0.204±0.00^{b}	0.196±0.00^{c}	0.208±0.00^{a}

Crude ash and mineral content of shell meals: There was no significant difference in crude ash, P and DM content of shell meals produced from different species and processing methods (Table 5). The shells contained considerably high levels of calcium, but very low amounts of phosphorous (<0.1% DM). The Ca content ranged from 31.4-36.5% based on dry matter (DM) weight. Raw shell meal derived from green mussel shells had the highest Ca (35.8%), followed by that from blood clams (35.0%) and lake mussels (34.4%). Raw meal from river mussel shells had the lowest Ca (31.4%). Meanwhile, the mean Ca content of roasted shell meal (35.8%) was significantly higher ($p<0.05$) than that of raw meal (34.1%) and the Ca content of roasted meals produced from the four different species did not significantly differ ($p>0.05$).

Nutritive values of shell meals quail fed diets supplemented with the different shell products showed no significant differences in feed intake, egg production and FCR (Table 6). However, the addition of shell meal to feed (P1, P2, P3) had a beneficial effect on egg shell quality. Quail fed diets containing shell meal (P1, P2, P3) showed significantly better egg shell quality ($p<0.05$) in terms of egg shell weight and thickness than those fed the control diet (P0). The best egg shell quality was seen for quail fed the diet supplemented with raw coarse meal (P3).

DISCUSSION

About half of the total body weight of shellfish can be attributed to the shell, which is between 31 and 36% mineral Ca. Here the percentage of dried shell depended on shellfish species and habitat, whereas, processing method affected grinding results. Lake mussels had the highest proportion of shell weight among the four species sampled, whereas, both fresh water and green mussels had higher shell weights compared to blood clams. Lake mussels also had the highest numerical content of crude ash, P and dry matter, although the values did not show statistically significant differences from that of the other three species (Table 5). These results are consistent with those of Zeswita *et al.*[22], who reported that fresh water mussels contained higher amounts of inorganic and organic material compared to sea shellfish. The higher percentage of dried shell as well as crude and mineral elements could be due to the favorable texture and organic content of the sediment substrate found in the habitat of this mussel, which is supported by geographic and environmental conditions in lakes and coastal estuaries in West Sumatra.

Mussels are benthic animals that live on bottom sediment composed of rich organic and soft muddy soil substrates[22]. The fertile soil substrates are carried by many rivers from agricultural land around the lakes. The favorable substrate texture and organic content in the lake sediment could also be impacted by cage aquaculture farming activities carried out in Lake Maninjau and Lake Singkarak that produce large amounts of organic material in the form of unconsumed feed and excreta from fish farming[23]. Meanwhile, the low percentage of dried shell seen for blood clams relative to the other species might be caused by factors present in coastal waters that could affect the growth rate and shell size of these clams, such as water temperature, food availability and reproductive activity[24].

Results for different grinding processes showed that raw coarse ground particles were associated with the highest meal yield rate. The coarse ground particles also had better physical properties in terms of bulk density and angle of response relative to raw fine particles and roasted meals. The higher bulk density and lower angle of response for raw coarse ground particles translates to more compact storage and better material flow, which are both important for efficient handling, mixing and automatic weighing of bulk material. Moreover, processing the shell into raw coarse particles positively affected nutritive values. Laying quail fed diets supplemented with raw coarse shell meals produced from lake mussels had the best egg shell weight, percentage and thickness (Table 6). These results supported previous studies of laying hens[12,13,25] that showed that large Ca-rich particles improve egg shell quality due to lessened *in vitro* solubility of Ca and longer retention in the gut, which promotes a more constant supply of calcium to the body during the night when most of the egg shell forms. Here, the better egg shell quality also appeared to be related to the favorable particle size distribution of the coarse particles in the raw coarse meal made from lake mussels that had distributions of fine, medium and coarse particles of 44.3, 33.5 and 22.6%, respectively (Table 4). Pizzolante *et al.*[12] reported that egg quality improved when up to 50% fine limestone was replaced with a combination of coarse limestone with oyster shell in laying hen feed, such that both pulverized and granular forms of calcium carbonate could be included in diets for laying hens to enhance egg quality.

Open-air burning prior to grinding of raw shells produced uniform roasted products with higher Ca content as well as the highest angle of response and lowest bulk densities (Table 4). The roasting produced meals that were mainly (77.5%) composed of fine particles ($\leq$0.25 mm) arising from breakdown of larger, irregularly-shaped particles that have coarser surfaces. The larger angle of response of roasted meal was related to particle size and surface characteristics, wherein a lower particle size combined with a coarse surface produces a higher angle of response. However, the bulk density, angle of response and particle size distribution of the roasted meals for all shell samples were essentially similar among the different species and habitats (Table 4). Particle size distribution is an important logistical factor as it influences efficiency of feed handling, processing and final product quality (e.g., stability, homogeneity and ingredient segregation). Feed particle size also in uences digestive enzyme activity and voluntary intake. Roasted shells showed constant particle size distribution among the different species and living habitats (Table 4, Fig. 2). The similar effects on mineral composition, physical properties and particle size distribution produced by open-air burning was also observed in a study by Khalil *et al.*[26] that examined production of bone char meal from cow bones.

The mean Ca content increased from 34.1% for raw fine shell meal to 35.8% for roasted meal and there was no significant difference in Ca content for the different shellfish species and habitats (Table 5). Similar findings were obtained by Khalil[15], who found that the Ca content of freshwater snail shells increased from 35.2-36.3% following open-air burning. In that study, feeding of roasted shell meal had better effects on egg shell weight and percentage of egg shell compared to a control diet supplemented with limestone meal. Here, the nutritive values of roasted shell meal were numerically better than raw fine meal in terms of egg production, FCR and egg shell quality, although the values were not significantly different for the different species and processing methods ($p>0.05$) (Table 6). Guinotte and Nys[27] reported that oyster shells have a reduced solubility rate relative to limestone. The results here indicated that the roasted shell meal might be potentially used as a mineral supplement in diets for monogastric livestock and ruminants. Khalil *et al.*[28] reported that supplementation of cattle feed with local minerals containing roasted mussel shells could improve body weight gain and feed utilization efficiency of heifers. Roasted shell meals could also be used as a raw material for various applications, including as a filler in polypropylene production[7], a construction material[29,30], production of calcium phosphate[31] and liming materials for crop production[32].

CONCLUSION

The percentage of dried shell weight depended on shellfish species and habitat, whereas grinding results were affected by the processing method. Raw coarse ground meals produced the highest percentage of meal yield, followed by raw fine meal and roasted meal. Burning raw shells prior to grinding produced a finer particle product with higher Ca content and uniform physical properties. The raw coarse meals had the best shell product with the highest meal yield rate and best physical properties as well as the best nutritive values for poultry feed.

SIGNIFICANCE STATEMENT

This study shows that simple processing of waste shells from shellfish in the province of West Sumatra could be used to produce a renewable local mineral feed for livestock. This study will help diversify shell products by application of thermal processing to ensure optimum utilization of otherwise discarded shells and increase the income of local fishermen.

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