

Interrelationship Among Methionine, Choline, and Betaine in Channel Catfish *Ictalurus punctatus*

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Abstract

The present research was conducted to evaluate if there is an interrelationship between methionine and choline as well as between betaine and choline in feed formulations for channel catfish. A semi-purified basal diet was formulated to contain 28-g crude protein/100-g diet. DL-methionine was added to the basal diet to produce deplete, sufficient, and replete levels of methionine (0.35%, 0.39%, and 0.43%); choline chloride (200, 400, and 600-mg choline/kg diet) was added to the basal diet to produce low, median, and high levels of choline; and free base betaine (0 and 1,000-mg betaine/kg diet) was added to the basal diet to produce sufficient and replete levels of betaine in eight experimental diets. Each diet was randomly fed to triplicate groups of fish (15 fish/each group) over a 13-wk growth trial. Added choline in the diets containing 0.35% (deplete) methionine had a significant linear effect on weight gain and feed consumption. There were no significant differences in weight gain, FCR, survival, HIS, and liver lipid between diet 3 (deplete methionine and high choline) and diet 6 (sufficient methionine and median choline). Both added choline and betaine in the diets containing 0.39% (sufficient) methionine had significant effects on weight gain, feed consumption, and FCR. There were no significant differences in the measured parameters between diet 7 (low choline and excess betaine) and diet 6 (median choline and no betaine). Methionine had no significant linear effect on weight gain and feed consumption when choline was low. Therefore, in the absence of sufficient methionine, choline or betaine can spare a portion of methionine requirement of channel catfish. In the absence of sufficient choline, methionine cannot spare choline requirement of channel catfish. Further, in the absence of sufficient choline, betaine can spare at least a portion of choline requirement of channel catfish.

When two or more nutrients in a fish diet are interrelated, it is necessary to consider how their presence and quantity will influence the growth of fish and economic benefits of fish production when one or all nutrients are supplemented to the diet.

Methionine is an essential amino acid that is required by fish (Lovell 1989). Methionine has three major metabolic functions: as an essential amino acid, which is required for protein synthesis; as a sulfur source, which is needed for synthesis of other sulfur-containing biochemicals; and as a methyl donor, which can provide methyl groups for use in methylation reactions (Mehler 1986). Dietary methionine requirements have been determined with various species of fish including channel catfish (Harding et al. 1977).

Choline is considered a vitamin in the diets

of vertebrate such as poultry, dogs, and several species of fish. Choline has three major metabolic functions: as a component of phosphatidylcholine; as a precursor of neurotransmitter acetylcholine; and as a precursor of betaine, which acts as a source of labile methyl groups for methylation reactions (NRC 1993). Dietary choline requirements have been estimated for several fish species including channel catfish (Wilson and Poe 1988).

Betaine is a non-toxic amino acid derivative found widely distributed in nature (Kettunen et al. 2001). Betaine has three major metabolic functions: as a methyl donor, which can provide methyl groups for essential biochemical reactions (Scott 1986); as an osmolyte, which can allow accumulation of a sufficient muscle betaine reserve so as to reduce the consequences of osmotic stress in fish (Virtanen et al., 1989; Clarke et al. 1994; Castrol et al. 1998); and as a feeding stimulant for several species of fish

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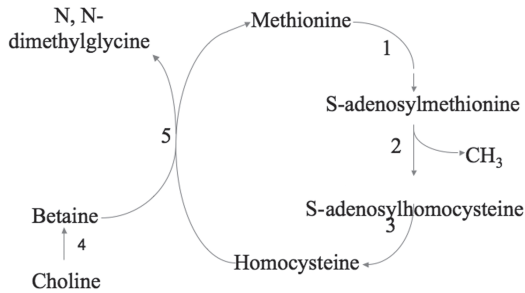


FIGURE 1. *Metabolism of methionine, choline and betaine* (Mehler, 1986). Numerals indicate the following enzymes: 1) methionine adenosyltransferase; 2) various enzymes; 3) *S*-adenosylhomocysteine hydrolase; 4) choline dehydrogenase; and 5) betaine-homocysteine methyltransferase.

and crustaceans (Virtanen et al. 1994; Coman et al. 1996; Knights 1996; Harpaz 1997; Papatryphon and Soares 2000).

Because methionine, choline, and betaine share a common metabolic use as methyl donors (Fig. 1), there may be an interrelationship among dietary methionine, choline, and betaine. Du Vigneaud et al. (1939, 1940, 1950) and Klose and Almquist (1941) postulated that once the requirements for methionine and choline per se are met, the metabolic requirement for labile methyl groups can be met by either methionine or choline or betaine. In the poultry industry, the interrelationships among methionine, choline, and betaine have been a subject of controversy among research workers for many years. Emmert et al. (1996), Schutte et al. (1997), and McDevitt et al. (1999) concluded that both choline and betaine were inefficient at sparing methionine in diets fed to chicks. However, Gerry et al. (1948), Quillin et al. (1961), Pesti et al. (1980), and Barker et al. (1982) reported in the absence of sufficient methionine, either choline or betaine can spare methionine in diets fed to chicks. Studies on the interrelationships among methionine, choline, and betaine in fish are scarce. Methionine is often one of the most limiting amino acids in ingredients used for fish feeds (Harris 1980). Because the price of methionine is higher than choline and betaine, it is important to use methionine for protein synthesis and to use choline or betaine

as methyl donor in metabolism. Therefore, a better understanding of the interrelationship among methionine, choline, and betaine may not only improve fish growth performance but also reduce the cost of feed.

The objective of the present research was to determine if there is an interrelationship between methionine and choline as well as between choline and betaine in feed formulations for the channel catfish.

Materials and Methods

Channel catfish fingerlings were obtained from a private producer in Alabama, and maintained at the North Auburn Fisheries Research Unit (Auburn, Alabama). Upon receipt of the fish, they were dipped into a solution of potassium permanganate (5 mg/L) for 5 min. Fish were then transferred into a semi-closed recirculating system which consisted of a series of 60-L aquaria. The system was equipped with a settling chamber biological filter, a rapid-rate sand filter, and a circulation pump. Aeration was provided via a regenerative air blower and submerged air diffusers.

Fish were acclimated to laboratory conditions for 2 wk before initiation of the experiment. Prior to the experiment, fish were fed a commercial diet twice daily to satiation. After the acclimation period, 15 fish (5.77 g mean initial weight) were randomly selected and stocked into each of 24 aquaria, and the study initiated. Experimental diets were randomly assigned to triplicate groups of fish. The diets were offered at a rate of approximate 4% of body weight daily divided into two equal feedings. Fish of each aquarium were weighed weekly, and the feed ration was adjusted accordingly.

Water temperature and dissolved oxygen (DO) were measured daily using a YSI-55 digital oxygen/temperature meter (YSI corporation, Yellow Springs, Ohio, USA). Total ammonia-nitrogen was determined using the Solorzano (1969) phenolhypochlorite method, and nitrite-nitrogen was estimated using the methods described by Boyd and Tucker (1992) every 2 wk. The pH was monitored daily using an electronic pH meter (pH pen; Fisher Scientific, Cincinnati, Ohio, USA). The pH of

the water was adjusted on an as need basis using sodium bicarbonate. Seasalt was added to maintain a low level of chloride ions (approximately 0.2 mg/L).

The basal diet (Table 1) used in the present experiment was formulated to contain 28% crude protein and 6% lipid. Casein, gelatin and corn gluten meal provided 13.07-g crude protein/100-g diet, and a crystalline amino acid mixture provided 14.93-g crude protein/100-g diet. Contribution of essential amino acids of the basal diet are listed in Table 2. The calculated and analyzed contents of methionine, choline, and betaine in the experimental diets are shown in Table 3. The contents of choline and betaine in the basal diet were analyzed by Danisco Animal Nutrition, Finland, and methionine content was analyzed by Experimental Station Chemical Laboratories, University of Missouri-Columbia, Missouri, USA. Total sulfur amino acid concentration in the basal diet was 0.61% (0.35% methionine and 0.26% cystine). The basal diet contained 0.35% methionine, thus meeting 90% of the dietary requirement of channel catfish for methionine (0.39%) as reported by Harding et al. (1977). The remaining dietary essential amino acid concentrations met or exceeded the essential amino acids requirements of channel catfish recommended by NRC (1993). A choline-free, but otherwise complete, vitamin premix and nutritionally complete mineral premix were added to the diets.

TABLE 1. Composition (as g/100 g dry weight) of the basal diet.

Ingredient ^a	Amount
Casein (vitamin free)	4.00
Gelatin	1.00
Corn gluten meal	12.50
Amino acid mixture ^b	14.93
Wheat starch	35.00
Cellulose	20.32
Carboxymethyl cellulose	2.00
Corn oil	6.00
Vitamin premix, choline-free ^c	2.00
Mineral premix ^d	0.50
Calcium phosphate, dibasic	1.75

^aObtained from U. S. Biochemical, Cleveland, Ohio, USA.

^bContained: L-cystine-HCl, 0.08; L-arginine-HCl, 0.70; L-histidine-HCl, 0.12; L-isoleucine, 0.15; L-lysine-HCl, 0.94; L-phenylalanine, 0.64; L-threonine, 0.09; L-tryptophan, 0.03; L-valine, 0.10; L-aspartic acid, 3.80; L-glutamic acid, 4.97; L-serine, 2.22; and L-proline, 1.09. L-Phenylalanine, L-aspartic acid, and L-glutamic acid were obtained from U. S. Biochemical, Cleveland, Ohio, USA, and the remaining amino acids were obtained from ICN Biomedicals, Irvine, California, USA.

^cContained (as g/kg): thiamin-HCl, 1.75; riboflavin, 1.00; pyridoxine-HCl, 1.82; pantothenic acid, hemicalcium salt, 10.92; nicotinic acid, 7.81; biotin, 0.10; folic acid, 0.27; vitamin B₁₂, 0.001; inositol, 20.00; L-ascorbic acid polyphosphate, 14.29; menadione sodium bisulfite, 0.96; vitamin A acetate, 0.62; vitamin D₃, 0.10; dl-alpha-tocopherol acetate, 10.53; alpha-cellulose, 929.843.

^dContained (as g/kg): cobalt chloride, 0.04; cupric sulfate pentahydrate, 2.50; ferrous sulfate, 40.00; magnesium sulfate anhydrous, 138.62; manganous sulfate monohydrate, 6.50; potassium iodide, 0.67; sodium selenite, 0.10; zinc sulfate heptahydrate, 131.93; cellulose, 679.64.

TABLE 2. Contribution (as g/100 g dry weight) of essential amino acids from basal diet.

Amino acid	Supplied by casein, gelatin, and corn gluten meal	Supplied by amino acid mixture	Total
Methionine	0.35	0.00	0.35
Cystine	0.18	0.08	0.26
Arginine	0.50	0.70	1.20
Histidine	0.30	0.12	0.42
Isoleucine	0.58	0.15	0.73
Leucine	1.80	0.00	1.80
Lysine	0.49	0.94	1.43
Phenylalanine	0.76	0.64	1.40
Threonine	0.47	0.09	0.56
Tryptophan	0.11	0.03	0.14
Valine	0.74	0.10	0.84

TABLE 3. Calculated and analyzed contents of methionine, choline, and betaine in the eight dietary treatments. The basal diet without supplemented choline and betaine contained 480-mg choline/kg diet and 480-mg betaine/kg diet. The contents of choline and betaine in basal diet were analyzed by Danisco Animal Nutrition, Finland.

Diet #	Methionine (%)			Choline supplemented (mg/kg diet)	Betaine supplemented (mg/kg diet)
	Calculated Content	Analyzed content ^a	Requirement status ^b		
1	0.35	0.35	-	200	0
4	0.39	0.40	=	200	0
2	0.35	0.37	-	400	0
5	0.43	0.44	+	200	0
3	0.35	0.35	-	600	0
6	0.39	0.40	=	400	0
7	0.39	0.41	=	200	1000
8	0.39	0.39	=	400	1000

^aMethionine content was analyzed by Experimental Station Chemical Laboratories, University of Missouri-Columbia, Missouri, USA.

^b-, =, and + were respectively used to represent deplete, sufficient, and replete concentrations.

DL-methionine was added to the basal diet to produce three concentrations of methionine (0.35%, 0.39%, and 0.43%); choline chloride (200, 400, and 600-mg choline/kg diet) was added to the basal diet to produce three concentrations of dietary choline (680, 880, and 1,080-mg choline/kg diet); and free base betaine (0 and 1,000-mg betaine/kg diet) was added to the basal diet to produce two concentrations of betaine in eight test diets (Table 3). Three methionine concentrations of 0.35%, 0.39%, and 0.43% were respectively regarded as deplete, sufficient, and replete concentrations of methionine for channel catfish in the present research. The diets supplemented with three choline concentrations of 200, 400, and 600-mg choline/kg diet were respectively regarded as the diets with low, median, and high concentrations of choline in the present research. The diets supplemented with two betaine concentrations (0 and 1,000-mg betaine/kg diet) were respectively regarded as the diets with no and excess concentrations of betaine in this trial. Dry ingredients were homogenized in a mixer for 20 min then hot water was added to produce a mash appropriate for pelleting. Before pelleting, diets were adjusted to pH 7.0 with saturated sodium hydroxide based on the methods

reported by Wilson et al. (1977). A 5-g portion of the diet was homogenized with 50 mL of water and pH was determined. NaOH solution (6 N) was added to the diet to establish a pH level of 7.0. All diets were then pelleted using 3-mm die, dried at 40 C in a forced-air oven for 24 h and stored at -20 C.

At the termination of the experiment, the fish were weighed 24 h after the final feeding. Then the fish were immersed in a solution of tricaine methanesulfonate (MS222; Argent Chemical, Redmond, Washington, USA) until euthanized. From each aquarium, fish were randomly collected and total body weight and liver weight per fish were recorded for calculation of hepatosomatic index (HSI = liver weight/body weight \times 100). Livers were then pooled by aquaria and frozen for subsequent analyses. Total liver lipid was determined for each pooled sample by homogenizing duplicate subsamples in chloroform/methanol (2:1, v:v) using a modification of the methods described by Folch et al. (1957). Moisture was determined in duplicate on a portion of the composite liver sample by drying to a constant weight at 95 C using the methods described by the Association of Official Analytical Chemists (1990).

Due to the treatment structures, two sepa-

rate analyses were run for the interrelationship between methionine and choline and the interrelationship between choline and betaine. The first analysis included six dietary treatments. This analysis used one-way ANOVA and Duncan's multiple range test to compare all six treatments (Table 4). Additionally, we applied contrasts to test the linear effect of methionine when choline is low, the linear effect of choline when methionine is depleted, and to test differences among specific treatments. In the second analysis (Table 5) a 2×2 factorial design was used to analyze the main effects of choline and betaine and interactions between choline and betaine. If differences in treatment means were detected by ANOVA, Duncan's multiple range test was used to determine difference between means. Statements of statistical significance were based on a probability of ($P \leq 0.05$). All tests were performed using the Statistical Analysis System (V 8.2, SAS Institute Inc. Cary, North Carolina, USA).

Results and Discussion

Averages and standard deviations for water quality variables were temperature, 30.6 ± 1.0 C; dissolved oxygen, 6.9 ± 0.7 mg/L; pH, 8.0 ± 0.2 ; total ammonia-nitrogen, 0.012 ± 0.007 mg/L; and nitrite-nitrogen 0.003 ± 0.001 mg/L. These values are typical for this type of research system and are well within the limits for acceptable water quality values for this species.

Fish fed diets 1, 2, 3, 4, 5, or 6 were analyzed to evaluate the interrelationship between methionine and choline by one-way ANOVA and contrasts (Table 4). Based on P -value of contrast among diets 1, 2, and 3, added choline in the diets containing 0.35% (deplete) methionine had a significant linear effect on weight gain and feed consumption. As added choline content in the diets containing 0.35% (deplete) methionine increased from 200 to 600 mg/kg diet, weight gain linearly increased from 239.3 to 280.3%, and feed consumption linearly increased from 34.2 to 37.2 g/fish. There were no significant differences in weight gain, FCR, survival, HSI, and liver lipid between diet 3 (deplete methionine and high choline) and diet 6 (sufficient methionine and median choline)

(Table 4). These results indicated that in the absence of sufficient methionine, choline can spare a portion of methionine requirement of channel catfish fed semi-purified diets.

In steps of metabolism of methionine, choline, and betaine (Fig. 1), methionine and ATP synthesize *S*-adenosylmethionine (SAM), which is the principle methyl group donor in vertebrate tissue. When SAM donates a methyl group it forms *S*-adenosylhomocysteine that is transformed to homocysteine. In order to recycle methionine, choline is first converted into betaine, and then betaine reacts with homocysteine to produce methionine and dimethylglycine in the presence of betaine-homocysteine methyltransferase (BHMT). In this step of metabolism, betaine donates a methyl group, forming dimethylglycine. Therefore, choline or betaine can reduce the amount of methionine required for methylation by providing the methyl groups for the regeneration of methionine from homocysteine. Because the physiological need for methionine often exceeds its availability in the diet, the methionine-sparing effect of the transmethylation cycle is very important (Krebs et al. 1976; Davies et al. 1992). Choline has been shown to be capable of sparing methionine in the diet of chicks (Klose and Almquist 1941; Gerry et al. 1948; Quillin et al. 1961; Pesti et al. 1980; Barker et al. 1982). The studies in metabolism of methionine, choline, and betaine, and results of research in chicks supported our conclusion that choline can spare a portion of methionine requirement of catfish.

Fish fed diet 2, 6, 7 and 8 were analyzed to evaluate the interrelationship between choline and betaine by 2×2 factorial design (Table 5). There were no interactions in weight gain, feed consumption, FCR, survival, HSI, and liver lipid content between added choline and added betaine. Added choline had significant effects on weight gain, feed consumption, and FCR. As added choline content in the diets containing 0.39% (sufficient) methionine increased from 200 to 400 mg/kg diet (total dietary choline of 680 to 880 mg/kg diet), weight gain significantly increased from 241.3 to 304.7%, feed consumption significantly increased from 34.9 to 39.4 g/fish, and FCR significantly decreased

TABLE 4. Response of channel catfish offered the experimental diets containing various contents of methionine and choline over a 13-wk growth trial. Values are means of three replicates. Means in the same column with different superscripts were significantly different ($P < 0.05$).

Diet #	Methionine		Choline added (mg/kg diet)	Weight gain ² %	Feed consumption (g/fish)	FCR ³	Survival (%)	HSI ⁴ (%)	Liver lipid ⁵ (%)
	(%)	Req. status ¹							
1	0.35	-	200	239.3 ^c	34.2 ^c	2.5 ^a	100.0 ^a	1.30 ^a	6.58 ^a
2	0.35	-	400	259.7 ^{bc}	35.3 ^{bc}	2.4 ^a	93.3 ^a	1.49 ^a	7.29 ^a
3	0.35	-	600	280.3 ^{ab}	37.2 ^b	2.4 ^a	91.0 ^a	1.57 ^a	6.13 ^a
4	0.39	=	200	241.3 ^c	34.9 ^{bc}	2.5 ^a	100.0 ^a	1.44 ^a	8.25 ^a
5	0.43	+	200	241.7 ^c	35.1 ^{bc}	2.5 ^a	97.7 ^a	1.70 ^a	7.05 ^a
6	0.39	=	400	304.7 ^a	39.4 ^a	2.2 ^a	97.7 ^a	1.40 ^a	9.40 ^a
PSE ⁶				11.47	0.73	0.09	3.87	0.16	1.46
				Probability					
Comparison of all treatments				0.0082	0.0028	0.2664	0.5105	0.6358	0.3051
Contrast <i>P</i> -values									
Choline linear effect (Diet 1, 2, and 3)				0.0274	0.0478	0.3366	0.2606	0.2271	0.7070
Methionine linear effect (Diet 1, 4, and 5)				0.9062	0.3971	0.8271	0.2666	0.1607	0.7193
Diet 3 vs Diet 6				0.1596	0.0476	0.3064	0.2461	0.4867	0.1425
Diet 5 vs Diet 6				0.0022	0.0012	0.0646	1.000	0.2306	0.2817

¹-, =, and + were respectively used to represent deplete, sufficient, and replete concentrations.

²% Weight gain = (final weight - initial weight) × 100/initial weight

³FCR = dry weight of feed offered/wet weight gain.

⁴HSI = Liver weight/body weight × 100.

⁵Expressed on a dry matter basis.

⁶PSE = pooled standard error.

TABLE 5. Response of channel catfish offered the experimental diets containing various contents of choline and betaine over a 13-wk growth trial. Values are means of three replicates. Means in the same column with different superscripts were significantly different ($P < 0.05$).

Diet #	Methionine (%)	Choline Added (mg/kg diet)	Betaine added (mg/kg diet)	Weight gain ¹ %	Feed consumption (g/fish)	FCR ²	Survival (%)	HSI ³ (%)	Liver lipid ⁴ (%)
6	0.39	400	0	304.7 ^b	39.4 ^{ab}	2.2 ^b	97.7 ^a	1.40 ^a	9.40 ^a
7	0.39	200	1000	295.3 ^b	37.9 ^b	2.2 ^b	97.7 ^a	1.57 ^a	9.47 ^a
8	0.39	400	1000	339.7 ^a	42.0 ^a	2.1 ^b	97.7 ^a	1.55 ^a	9.74 ^a
PSE ⁵				8.54	0.86	0.05	2.02	0.12	1.67
				Probability					
Main effects and interactions									
Choline				0.0002	0.0011	0.0036	0.5796	0.8230	0.6838
Betaine				0.0008	0.0125	0.0036	0.5796	0.2596	0.6535
Choline × Betaine				0.2981	0.7981	0.0904	0.5796	0.9553	0.8019

¹% Weight gain = (final weight - initial weight) × 100/initial weight

²FCR = dry weight of feed offered/wet weight gain.

³HSI = Liver weight/body weight × 100.

⁴Expressed on a dry matter basis.

⁵PSE = pooled standard error.

from 2.5 to 2.2. These results were in agreement with those of Zhang and Wilson (1999), who reported that as choline supplements were increased from 0 to 700 mg/kg diet, weight gain significantly increased from 164 to 289%. Based on response of weight gain to dietary choline level, dietary choline level (680 mg/kg diet) in this trial did not meet the choline requirement of catfish for maximum growth. This level is higher than that of Zhang and Wilson (1999), who reported that based on response of liver choline to dietary choline, choline requirement of catfish was 429 ± 35 mg/kg diet.

Added betaine had a significant effect on weight gain, feed consumption, and FCR (Table 5). As added betaine in the diets containing 200-mg choline/kg diet increased from 0 to 1000 mg/kg diet, weight gain significantly increased from 241.3 to 295.3%, feed consumption significantly increased from 34.9 to 37.9 g/fish, and FCR significantly decreased from 2.5 to 2.2. There were no significant differences in weight gain, feed consumption, FCR, survival, HIS, and liver lipid content between diet 7 (low choline and excess betaine) and diet 6 (median choline and no betaine) (Table 5). These results indicated that in the absence of sufficient choline, betaine can spare at least a portion of the choline requirement of channel catfish fed semi-purified diets. Rumsey (1991) concluded that half of the choline requirement of rainbow trout can be spared by betaine. Kasper *et al.* (2002) found that the dietary betaine can spare the entire choline requirement of juvenile tilapia fed a chemically purified diet. These studies strongly support our conclusion that choline can be spared by betaine in catfish. In addition to functioning as a methyl donor, betaine is known as a flavor attractant and osmolyte for some species of fish and crustacean. Kasper *et al.* (2002) reported that a significant increase in feed consumption was used to evaluate betaine as a flavor additive. However, the function of betaine as flavor additive was not the focus of the present experiment. The feeding rate was restricted to approximate 4 % body weight of fish, and all eight diets were observed to be eaten by fish within 3 min in the present study. The function

of betaine as a flavor additive was restricted in the present study.

In major steps of choline metabolism (Fig. 1), choline first has to be converted to betaine so that its methyl groups will be available in cellular reactions that require methyl groups. Oxidation of choline to betaine is considered a one-way reaction (Scott 1986). Because choline can spare a portion of the methionine requirement and betaine can spare a portion of choline requirement in catfish, betaine can spare a portion of methionine requirement of catfish in the absence of sufficient dietary methionine. Similar to our results in catfish, Virtanen and Rosi (1995) reported that betaine might have a methionine sparing effect in chicks.

Based on *P*-value of contrast among diets 1, 4, and 5, methionine had no significant linear effect on weight gain and feed consumption when choline was limited (Table 4). This result was in agreement with those of Wilson and Poe (1988), who reported that weight gain of catfish was not significantly affected by methionine. There were significant differences in weight gain and feed consumption between diet 5 (replete methionine and low choline) and diet 6 (sufficient methionine and median choline) (Table 4). Therefore, in the absence of sufficient choline, methionine cannot spare choline requirement of channel catfish fed semi-purified diets. Jukes *et al.* (1945) reported that because chicks appeared to be unable to methylate ethanolamine, chicks cannot utilize methionine to spare choline unless methylethanolamine is present. Similarly, Ketola (1976) and Rumsey (1991) concluded that because rainbow trout and lake trout cannot methylate ethanolamine to methylethanolamine, choline cannot be spared by methionine in these two species of fish. In addition, Wilson and Poe (1988) reported that although most animals can synthesize choline if adequate methyl donors such as methionine are present in the diet, the rate of choline synthesis has been shown to be insufficient to meet the metabolic and physiological need in some fast growing young animals. These studies supported our conclusion that methionine cannot spare choline in fingerling channel catfish.

Based on results of the present study, we concluded that in the absence of sufficient methionine, a portion of methionine requirement of channel catfish can be spared by choline or betaine. In the absence of sufficient choline, methionine cannot spare the choline requirement of channel catfish. Further, in the absence of sufficient choline, betaine can spare at least a portion of the choline requirement of channel catfish.

Acknowledgments

The authors would like to thank those who have taken the time to critically review this paper, as well as students and staff who helped to support this research. This research was supported in part by the Alabama Catfish Producers Association and Danisco Animal Nutrition. The mention of trademarks or proprietary products does not constitute an endorsement of the product by Auburn University and does not imply its approval to the exclusion of other products that may be suitable.

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