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Utilization of diets with hydrolyzed potato starch, or glucose by juvenile white sturgeon (*Acipenser transmontanus*), as affected by Maillard reaction during processing

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Abstract

An 8-week growth trial was conducted to study carbohydrate utilization by white sturgeon fed diets containing glucose or hydrolyzed potato starch (HPS). Four diets supplemented with 15% or 30% of glucose or HPS and a control diet with no added carbohydrate were each fed to triplicate groups of fish. The diets were processed by a 3-min 80 °C microwave moist heating, followed by 1-h 70 °C drying. Feeding rates varied from 1.7% to 3.2% body weight day^{-1} so that all treatment groups were fed the same amount of dietary protein and lipid. The HPS groups showed the highest ($P<0.05$) specific growth rate, followed by the control, and then by the glucose groups. Feed efficiency was highest in the control and 15% HPS group followed by the 30% HPS group, and lowest in the glucose groups. Protein and energy retentions, whole body lipid, and muscle glycogen showed a similar pattern; with the glucose groups significantly lower than the control and HPS groups, whereas there was no difference among the control and HPS groups. A lower lysine and glucose in the glucose than control diets suggested that a severe Maillard reaction had occurred in the moist heat process, drying, and storage of the glucose diets. This is supported by the significantly lower plasma lysine concentrations in sturgeon fed the glucose diets than those fed the control diet. Sturgeon fed the glucose diets also showed significantly lower concentrations of plasma protein, cysteine, and hydroxyproline than those fed the control diet, whereas concentrations of liver glycogen and plasma alanine, γ-aminobutyric acid and proline were significantly higher in sturgeon fed the glucose than the control and HPS diets. In conclusion, growth performances of sturgeon were not adversely affected by 15% HPS in the diet but severe Maillard reaction in the glucose diets resulted in significant reduction in the growth performances of the fish.

Keywords: White sturgeon; Hydrolyzed potato starch; Glucose; Plasma lysine; Maillard reaction

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1. Introduction

Carbohydrate utilization varies among fish species and is also affected by complexity, type, source, level, and heat treatment of the carbohydrate (NRC, 1993; Wilson, 1994; Shiau, 1997; Hemre et al., 2002). Common carp, red sea bream (Furuich and Yone, 1982), Nile tilapia (Anderson et al., 1984), yellowtail (Furuichi et al., 1986), channel catfish (Wilson and Poe, 1987), and hybrid tilapia (Tung and Shiau, 1991) grew better when fed a starch than a glucose diet. Chinook salmon (Buhler and Halver, 1961) and rainbow trout (Hung and Storebakken, 1994), however, grew better when fed a glucose than a starch diet. Hung et al. (1989) also showed a better energy retention in juvenile white sturgeon fed a glucose than a starch diet, and the diets were pelleted at room temperature and stored at −20 °C until fed.

Heat treatment is known to improve starch utilization by animals, and most fish species studied can utilize cooked starch better than raw starch (Wilson, 1994). Maillard-type reactions, however, can occur in animal feeds between reducing sugars and the amino group of amino acids, especially lysine, in the protein during moist heat treatment and storage. The loss in nutritional quality caused by Maillard reactions are attributed to destruction in essential amino acids, decreased digestibility, and eventually production of antinutritional and toxic components (Friedman et al., 1989). Products of the Maillard reaction are resistant to digestive enzymes of animals, and thus reduce the quality of dietary protein (Tanaka et al., 1977). There is a paucity of information on the effect of Maillard reaction on the quality of fish feeds (Plakas et al., 1985, 1988; Chen et al., 1987; Chuang and Lee, 1992). Plakas et al. (1985) showed a 46%, 61%, and 37% reduction in weight gain, feed efficiency, and protein deposited, respectively, in rainbow trout fed a mixture of protein isolate and glucose stored for 40 days at 37 °C when compared to those fed a control diet which was stored at −20 °C until fed. Plakas et al. (1988) also concluded that plasma lysine concentration is a sensitive in vivo measurement for the severity of the Maillard reaction. The original intention of the present study was to compare the ability of juvenile white sturgeon to utilize glucose and hydrolyzed potato starch (HPS). However, due to the unintended occurrence of Maillard reaction in our glucose diets we changed our objective to study the effect of Mallard reaction on the carbohydrate utilization by sturgeon.

2. Materials and methods

2.1. Diet preparation

A control diet containing no supplemental carbohydrate and four experimental diets containing 15% or 30% of hydrolyzed potato starch (gelatinization grade 75) (HSP-15, HSP-30) or glucose (G-15, G-30) were prepared (Table 1). The diet ingredients were mixed into dough, pressed through a spaghetti machine as strings, and passed through a microwave system for 3 min at 80 °C and 1450 MHz electromagnetic waves (Hemre et al., 2000). Strings were then cut into 2 mm pellets by an automatic cutter and the pellets were air-dried for 1 h at 70 °C to reduce moisture content to less than 100 g kg^{-1} Proximate composition of the diets was determined by AOAC methods (Jones, 1984), and dietary starch was measured after enzymatic degradation as described by Hemre et al. (1989), and dietary glucose was measured by a Tech-

Table 1
Formulation and composition of diets

	Control	HPS-15	HPS-30	G-15	G-30
Formulation (g kg^{-1})					
Minced saithe/squid (9:1)	959	914	857	913	857
Corn oil/fish oil (1:1)	35	35	30	34	30
Hydrolyzed potato starch	0	45	103	0	0
Glucose	0	0	0	45	103
Others[a]	9	9	9	9	9
Compositions (g kg^{-1})					
Moisture	40	10	10	30	40
Crude protein	630	540	460	560	450
Crude lipid	220	190	140	190	150
Ash	150	130	120	120	90
Starch	ND	143	307	–	–
Glucose[b]	4	–	–	67	177
Lysine	28	16	13	13	7
Calculated lysine level	28	24	20	25	20

[a] Others:30 g kg^{-1} each of vitamin premix, mineral premix (NRC, 1993), and polyvinylphosphate.

[b] Analysed glucose levels in diets G-15 and G-30 were reduced to half of the intended level, most likely due to the Maillard reaction (glucose bound to amino acids in the protein).

nicon RA1000 system according to method No. SM4-0123K86 (Technicon Instruments Corporation, Tarrytown, NY). Dietary amino acids were analyzed by the Pico Tag® method (Waters Alliance, Milford, MA) with prechromatographic offline derivatization with phenylisothiocyanate after acid hydrolysis (Ng and Hung, 1994). The amino acids were separated by high pressure liquid chromatography and detected by spectroscopy at 254 nm (Waters Alliance 2695, 2690 Separation Module). Pellet stability in water was tested at room temperature by weighing out 100 g and transferring to a beaker with 1 l water. After an hour, pellets and water samples were collected, and water was analyzed by a spectrophotometer at 260 nm for organic components (Shimadzu, UV-1601, Kyoto, Japan). Very little leaching of nutrients was found in the water, and fresh pellets and those kept in water for an hour had similar proximate composition.

2.2. Animal maintenance

Juvenile white sturgeon (*Acipenser transmontanus*) were obtained from a local farm and fed a commercial salmonid diet (Biodiet, bioproducts, Warrenton, OR) for 1 month at the facility of the Center for Aquatic Biology and Aquaculture, University of California, Davis. Twenty-five fish were distributed into each of 15 circular fiberglass tanks (66 cm diameter, 27 cm height, water volume 90 l) with a water temperature and flow rate of 18.5 ± 0.2 °C and 4 l min^{-1}, respectively (Hung and Lutes, 1987). The sturgeon were weaned gradually to an equal mixture of the experimental diets and acclimatized to the experimental conditions for a week. The growth trial was conducted between August 5th and October 1st, 1997 under a natural photoperiod (light/dark cycle of 13 h:11 h). General care, maintenance, and handling of sturgeon followed procedures approved by the Campus Animal Use and Care Administrative Advisory Committee at the University of California, Davis.

At the beginning of the trial, sturgeon were first transferred to 3 large tanks, captured randomly, weighed as a group, and transferred to each of the 15 tanks. Initial body weight of the sturgeon ranged from 25 to 27 g. Each of the diets was randomly assigned to three replicate tanks and the diet was dispensed daily by an automatic feeder (Hung and Lutes, 1987). Feeding rates of the 30% carbohydrate diets were pre-determined according to Cui and Hung (1995) based on body weight and water temperature. Sturgeon from the different groups were fed the same amount of protein and lipid but varied in energy from carbohydrate. This was achieved by adjusting the feeding rates for 0% and 15% carbohydrate diets to 70% and 85%, respectively, of the 30% carbohydrate diets. Sturgeon were weighed once every 2 weeks and feeding rates were adjusted accordingly, and there was no feeding on the day of weighing.

2.3. Sample collection and chemical analyses

Initial and final sampling followed the same procedure described by Fynn-Aikins et al. (1992) except that three groups of three fish were sampled for the initial body composition. Initial samples of blood were collected from 12 fish with 4 fish per pooled sample and within 4 h after the last feeding. At the end of the growth trial, fish were weighed and then blood, liver, and muscle were sampled from four fish per tank after the last feeding as described by Hung et al. (1989). After a 24 h fasting, three additional fish from each tank were sampled for determination of whole body proximate composition. Carcass, viscera, muscle, and liver were dissected, weighed, frozen in liquid nitrogen and stored at −80 °C from another three fish, and organ weights were used to calculate different morphometric indexes. Feed glucose and starch, and liver and muscle glycogen were measured according to the method of Murat and Serfaty (1974) except that glucose was measured by a Sigma kit (Sigma Chemical, St. Louis, MO). This glucose method can not detect glucose bound to other components, e.g. glucose bound to lysine after feed processing would no longer be detectable (see feed composition Table 1, analyzed values). Plasma glucose, protein and triacylglycerol were analyzed by methods described by Fynn-Aikins et al. (1992), and plasma free amino acids were determined by the Pico Tag® method (Ng and Hung, 1994).

2.4. Statistics

Data were analyzed by the General Linear Models procedure in the SAS computer software (SAS Institute Inc., Gary, NC). Results were subject to one way

Table 2
Growth performances of sturgeon fed different diets for 8 weeks[1]

	Control	HPS-15	HPS-30	G-15	G-30
SGR[2]	2.33 ± 0.09^{b}	2.86 ± 0.13^{a}	2.72 ± 0.10^{a}	0.22 ± 0.10^{c}	0.02 ± 0.04^{c}
FE[3]	1.44 ± 0.05^{a}	1.50 ± 0.11^{a}	1.21 ± 0.04^{b}	0.08 ± 0.04^{c}	0.01 ± 0.01^{c}
PR[4]	29.2 ± 1.8^{a}	30.6 ± 6.3^{a}	38.1 ± 10.9^{a}	-0.8 ± 0.8^{b}	-0.5 ± 0.2^{b}
ER[5]	37.2 ± 0.7^{a}	43.1 ± 0.9^{a}	39.2 ± 5.2^{a}	-1.2 ± 1.3^{b}	-4.4 ± 0.8^{b}

[1] Values are means ± S.D., $n=3$. Means with different superscripts in each row are significantly ($P<0.05$) different by the Scheffe's post-hoc test. Initial average body was 26.2 ± 0.9 g ($n=24$).
[2] SGR: specific growth rate = 100 (ln BW_f − ln BW_i) day^{-1}, where BW_f and BW_i are average final and initial body weights.
[3] FE: feed efficiency = (wet weight gain) (amount of dry diet offered)$^{-1}$.
[4] PR: protein retention = 100 (increase of body protein) (amount of dietary protein offered)$^{-1}$.
[5] ER: Energy retention = 100 (increase of body total energy) (amount of energy offered)$^{-1}$.

analysis of variance and significant differences at $P<0.05$ were subjected to Scheffe post-hoc test.

3. Results

The specific growth rate of sturgeon fed the HPS diets was significantly higher than those fed the control diet, which in turn was higher than those fed the glucose diets (Table 2). Sturgeon fed the control and HPS-15 diets had the highest feed efficiency, followed by those fed the HPS-30 diet, which in turn was higher than those fed the glucose diets. Protein and energy retentions and whole body lipid (Table 3) showed a similar pattern; with the glucose groups significantly lower than the control and HPS groups, whereas there was no difference among the control and HPS groups. Muscle glycogen, on the other hand, showed the opposite pattern with the glucose groups higher than the HPS and control groups. Plasma lysine concentrations of the glucose groups were significantly lower than the control group, whereas those of the HPS groups were intermediate and not different from either the glucose or control groups (Table 4). Sturgeon fed the glucose diets also showed a significantly lower concentration of plasma protein, cysteine, and hydroxyproline than those fed the control diet, whereas significantly higher concentrations of liver glycogen and plasma alanine, γ-aminobutyric acid and proline were observed in the glucose than control groups.

Table 3
Whole body composition, liver and muscle glycogen, and plasma glucose, protein and triacylglycerol of sturgeon fed different diets for 8 weeks[1]

	Control	HPS-15	HPS-30	G-15	G-30
Whole body (g kg^{-1})					
Moisture	$784 \pm 3^{a,b}$	749 ± 43^{b}	$776 \pm 6^{a,b}$	835 ± 9^{a}	831 ± 4^{a}
Lipid	70 ± 3^{a}	87 ± 17^{a}	76 ± 6^{a}	39 ± 6^{b}	39 ± 1^{b}
Crude protein	$112 \pm 2^{a,b}$	124 ± 19^{a}	110 ± 3^{abc}	81 ± 5^{c}	90 ± 3^{bc}
Ash	22 ± 1	20 ± 2	25 ± 7	24 ± 2	27 ± 1
Glycogen (mg g^{-1})					
Liver	14.3 ± 3.5^{c}	38.4 ± 12.2^{bc}	68.3 ± 3.0^{a}	48.2 ± 12.7^{ab}	76.1 ± 0.7^{a}
Muscle	0.45 ± 0.15^{b}	0.54 ± 0.17^{b}	1.01 ± 0.08^{b}	2.66 ± 0.32^{a}	2.04 ± 0.74^{a}
Plasma (mg dl^{-1})					
Glucose	91.7 ± 13.4	82.6 ± 8.1	97.9 ± 20.7	82.3 ± 20.7	80.0 ± 6.4
Protein	28.1 ± 7.3^{a}	25.8 ± 2.2^{ab}	29.0 ± 5.9^{a}	11.3 ± 2.1^{b}	8.1 ± 0.3^{c}
Triacylglycerol	1509 ± 309^{ab}	1594 ± 438^{ab}	1782 ± 613^{a}	815 ± 237^{b}	325 ± 31^{c}

Means with different superscripts in each row are significantly ($P<0.05$) different by the Scheffe's post-hoc test. Initial body moisture, lipid, protein and ash (g kg^{-1}) were 816 ± 20, 53 ± 4, 95 ± 12, and 21 ± 3, respectively, and initial liver and muscle glycogen were 32.9 ± 6.6 and 0.25 ± 0.10 mg g^{-1}, respectively.
[1] Values are means ± S.D., $n=3$.

t4.1 Table 4
t4.2 Major amino acid concentration in plasma of sturgeon fed different diets for 8 weeks[1]

t4.3		Control	HPS-15	HPS-30	G-15	G-30
t4.4	*EAA (nmol ml^{-1})*[2]					
t4.5	Lysine	158.5 ± 16.6^{a}	114.9 ± 10.7^{ab}	108.4 ± 25.7^{ab}	56.1 ± 32.6^{b}	54.3 ± 12.8^{b}
t4.6	Methionine	64.2 ± 7.0^{ab}	106.8 ± 19.7^{a}	100.8 ± 27.2^{a}	18.9 ± 1.2^{bc}	6.9 ± 5.9^{c}
t4.7	Arginine	119.1 ± 10.6^{a}	95.1 ± 17.7^{a}	84.1 ± 11.9^{ab}	81.7 ± 13.7^{ab}	37.5 ± 3.0^{b}
t4.8	Threonine	134.0 ± 9.6^{a}	106.7 ± 20.4^{ab}	99.1 ± 17.3^{ab}	100.5 ± 14.7^{ab}	71.1 ± 14.1^{b}
t4.9						
t4.10	*NEAA (nmo ml^{-1})*[2]					
t4.11	Alanine	221.9 ± 15.8^{b}	244.8 ± 19.9^{b}	246.6 ± 48.3^{b}	503.8 ± 34.3^{a}	452.6 ± 32.9^{a}
t4.12	γ-Aminobutyric acid	28.2 ± 4.6^{b}	51.5 ± 3.7^{b}	28.5 ± 7.2^{b}	382.9 ± 10.3^{a}	400.0 ± 151.7^{a}
t4.13	Proline	41.5 ± 14.4^{b}	37.5 ± 6.5^{b}	39.6 ± 3.0^{b}	140 ± 11.1^{a}	93.8 ± 13.3^{a}
t4.14	Homocysteine	11.0 ± 2.1^{a}	9.5 ± 1.0^{ab}	6.7 ± 2.5^{ab}	7.4 ± 4.0^{ab}	2.6 ± 1.6^{b}
t4.15	Cysteine	19.8 ± 0.0^{a}	18.7 ± 1.6^{a}	17.8 ± 4.5^{a}	ND^{b}	ND^{b}
t4.16	Hydroxyproline	181.0 ± 12.2^{a}	227.7 ± 20.4^{a}	213.9 ± 38.0^{a}	52.7 ± 9.0^{b}	39.8 ± 3.3^{b}

Means with different superscripts in each row are significantly ($P<0.05$) different by the Scheffe's post-hoc test. Initial plasma amino acids (nmol ml^{-1}) were: lysine, 127.5 ± 21.9; methionine, 95.5 ± 5.2; arginine, 117.6 ± 8.4; threonine, 164.5 ± 5.0; alanine, 377.3 ± 86.3; t4.17 γ-aminobutyric acid, 496.4 ± 91.2; cysteine, 27.3 ± 10.0; homocysteine, 10.6 ± 2.4; proline, 201.7 ± 11.3; and hydroxyproline, 62.2 ± 14.9.
t4.18 [1] Values are means ± S.D., $n=3$.
t4.19 [2] EAA: Essential amino acids, NEAA: Non essential amino acid.

Morphometric indexes (data not shown), whole body moisture and protein, and plasma triacylglycerol, methionine, arginine, threonine, and homocysteine concentrations were significantly affected by the dietary treatments but they did not show the distinct pattern similar to other parameters, and there was no significant difference in whole body ash or plasma glucose concentration among the treatment groups.

4. Discussion

The higher growth rate of sturgeon fed HPS-15 and HPS-30 than those fed the control diets was a result from the extra energy supplied by the heat treated hydrolyzed potato starch and not from protein or lipid, because the same amount of these nutrients were supplied to all three groups by varying their feeding rates. Interestingly, sturgeon fed the HPS diets had a better growth rate and feed efficiency than those fed a similar diet in our previous studies (Hung et al., 1989; Stuart and Hung, 1989; Fynn-Aikins et al., 1992; Lin et al., 1997). The higher growth and feed efficiency may have resulted from the dietary carbohydrate and protein source, processing method, and feeding rate. In the previous studies, raw corn starch or dextrin, casein (31%), wheat gluten (15%) and egg white (4%) were used as the dietary carbohydrate and protein source, whereas in the present study HPS, approximately 50% protein supplied by minced saithe/squid (9:1). The diets used in the previous studies were pelleted and dried at room temperature, whereas the diets used in the present study were processed by a 3-min 80 °C microwave moist heating and 1-h 70 °C drying. Finally, fish were fed 2% body weight day^{-1} in the previous study but they were fed 1.7% to 3.2% body weight day^{-1}. The exact reason for the improved growth performances of sturgeon fed the HPS diets, however, is not certain, and further studies are needed to identify the major beneficial factors.

Our results suggested that a severe and mild Maillard reaction had occurred in the glucose and HPS diets, respectively, because of the moist heat and drying processes, as suggested by the lower than expected lysine level in these diets. A mild Maillard reaction in the HPS diets is indicated by the similar plasma lysine concentrations, a sensitive biological index for Maillard reaction in rainbow trout feed (Plakas et al., 1988), among the HPS and control groups. Furthermore, there was no adverse effect on sturgeon fed the HPS-15 diet because their body composition, morphometric indexes, liver and muscle glycogen, and plasma glucose, protein, triacylglycerol, and important essential and non-essential amino acid concentrations were not different from those fed the control diet. Sturgeon fed the

HPS-30 diet also appeared normal and the above parameters were similar to those fed the control diet except that the HPS-30 group had a higher liver glycogen and lower feed efficiency. The higher liver glycogen content should not be considered as an adverse effect as discussed by Fynn-Aikins et al. (1992, 1993) and Kaushik et al. (1989), and because sturgeon fed these diets still grew better than those fed the control diet. Plasma glutamic oxalacetic transaminase and glutamic pyruvic transaminase activities have previously been found useful as an indication of leakage from liver and thus a damaged liver function in sturgeon (Fynn-Aikins et al., 1993). The higher liver glycogen did not seem to affect the liver function of the sturgeon fed the HPS-30 diets because the activity of these two enzymes in their plasma were not different from those fed the HPS-15 and control diets (Deng, unpublished data). The only reason precluding us to recommend up to 30% HPS in sturgeon diet, thus was the lower feed efficiency than those fed the control and HPS-15 diets.

Utilization of HPS has been studied in several species of fish. Jeong et al. (1992) showed that growth rate, feed efficiency, and protein efficiency ratio of rainbow trout were increased by increasing dietary gelatinized potato starch levels, with a plateau around 40%. Similar growth performances were obtained by Takeuchi et al. (1990) in rainbow trout and common carp fed diets containing 30% gelatinized potato starch. Our results showed that sturgeon grew well with up to 30% HPS in the diet but with a lower feed efficiency than those fed the control and HPS-15 diets. This was similar to results reported by Furuichi et al. (1986), where the growth of yellowtail in the 20% gelatinized potato starch group did not differ from the 10% group but the feed efficiency was lower in the 20% group. Hemre et al. (1989), however, showed a poor utilization of gelatinized potato starch by cod. No significant increase in energy retention with increased carbohydrate inclusion levels was observed in the above studies. Hemre et al. (2000) also observed that the growth of juvenile Atlantic salmon was not affected by feeding the same HPS diets as used in the current study but the feed efficiency and protein efficiency ratio decreased with the increase of HPS from 15% to 30% in the diets. Bureau et al. (1997) suggested that the energy from the gelatinized potato starch was poorly retained in rainbow trout and a significant proportion may have been lost in urine.

Our results showed that sturgeon fed the glucose diets had significantly lower growth performance than those fed the control and HPS diets. This was contradictory to our previous studies because no adverse effects on growth performance was observed in sturgeon fed diets with 27–35% glucose (Hung et al., 1989; Fynn-Aikins et al., 1992). The poor growth was not due to low feed intake because the sturgeon readily accepted and consumed the diets. The poor growth performance thus is ascribed to a severe Maillard reaction between glucose and protein-bound lysine during the microwave moist heating, and subsequent hot air drying. This is supported by the 52% and 35% lower than expected level of lysine, respectively, and the more than 40% lower than expected level of glucose in the G-15 and G-30 diets.

Severe Maillard reaction is known to lower utilization of the diets because of the lower digestibility/availability of some essential amino acids, especially lysine. The poor growth performances and low plasma lysine concentrations of sturgeon fed the glucose diets agreed with a previous study by Plakas et al. (1985) who showed a depressed growth and lower digestibility of amino acids in rainbow trout fed diets where Maillard reaction had occurred. Furthermore, Plakas et al. (1988) also showed that plasma free lysine response is a sensitive in vivo index of the reduced availability of lysine in the dietary protein as a result of Maillard reaction. This experiment was not designed primarily to study effects of Maillard products on the fish. Thus, further studies are needed to find out if the reduced performance of the sturgeons was only due to insufficient supply of essential amino acids, mainly lysine, or if toxic Maillard products negatively impacted the metabolism of the fish.

In conclusion, our results indicated that under restricted feeding, juvenile white sturgeon can utilize up to 30% HPS but they showed a better feed efficiency with 15% HPS. On the other hand, the 3-min 80 °C microwave moist heating and 1-h at 70 °C drying was shown to cause a severe Maillard reaction reducing the protein quality of the glucose diets, which in turn caused significant reduction in the growth performance of the sturgeon.

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