

Scotland's Rural College

Effect of phytase on growth performance, phytate degradation and gene expression of myo-inositol transporters in the small intestine, liver and kidney of 21 day old broilers

Walk, CL; Bedford, MR; Olukosi, OA

Published in:
Poultry Science

DOI:
[10.3382/ps/pex392](https://doi.org/10.3382/ps/pex392)

First published: 12/02/2018

Document Version
Peer reviewed version

[Link to publication](#)

Citation for published version (APA):

Walk, CL., Bedford, MR., & Olukosi, OA. (2018). Effect of phytase on growth performance, phytate degradation and gene expression of myo-inositol transporters in the small intestine, liver and kidney of 21 day old broilers. *Poultry Science*, 97(4), 1155 - 1162. <https://doi.org/10.3382/ps/pex392>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 **Effect of phytase on growth performance, phytate degradation and gene expression of**
2 ***myo*-inositol transporters in the small intestine, liver and kidney of 21 day old broilers**

3 C. L. Walk¹, M. R. Bedford¹ and O. A. Olukosi²

4 ¹ AB Vista, Marlborough Wiltshire, UK

5 ² Monogastric Science Research Centre, Scotland's Rural College, Edinburgh, EH9 3JG, UK

6 Corresponding author: carrie.walk@abvista.com

7 Running head: Superdoses of phytase and *myo*-inositol transporters

8 **ABSTRACT** An experiment was conducted to evaluate phytase on growth performance,
9 phytate degradation and the gene expression of *myo*-inositol transporters in 21-day old
10 broilers. Ross 308, male broilers (n = 240) were obtained and assigned to one of four diets,
11 with 10 pens/diet and six birds/pen from day one to 21. The diets consisted of a negative
12 control (NC) formulated to meet or exceed Ross 308 nutrient requirements, with the
13 exception of calcium (Ca) and available P (avP), which was reduced by 0.16 and 0.15%,
14 respectively. The NC diet was supplemented with 0, 500, 1,500 or 4,500 FTU/kg of phytase
15 to create four experimental diets. On day 21, all birds per pen were euthanized to obtain
16 digesta and tissue samples for phytate degradation and gene expression. Data were analysed
17 as an analysis of variance using the fit model platform in JMP v 13.0. The model included
18 phytase and significant means were separated using orthogonal linear and quadratic contrasts.
19 Phytase supplementation increased gain (linear, $P < 0.05$) but had no effect on feed intake or
20 feed conversion ratio. Phytate (IP6; quadratic, $P < 0.05$), phytate ester (IP5, IP4, IP3;
21 quadratic, $P < 0.05$) and inositol (linear, $P < 0.05$) concentration in the gizzard was
22 influenced by phytase supplementation. Phytase supplementation decreased IP6 (linear, $P <$
23 0.05) and IP5, IP4, IP3 (linear or quadratic, $P < 0.05$) and increased inositol (quadratic, $P <$
24 0.05) concentration in the ileal digesta. The expression of the H⁺-dependent *myo*-inositol
25 transporter, HMIT, was decreased (linear, $P < 0.05$) in the kidney and increased (linear, $P <$
26 0.05) in the ileum as phytase dose increased. Expression of the sodium-dependent *myo*-
27 inositol transporter, SMIT2, increased in the liver (quadratic, $P < 0.10$) and the jejunum
28 (quadratic, $P < 0.05$) as phytase dose increased. Intestinal alkaline phosphatase expression
29 increased in the ileum (linear, $P < 0.05$) as phytase dose increased. The influence of phytase
30 on phytate, phytate esters and inositol may influence intestinal alkaline phosphatase activity
31 and the expression of *myo*-inositol transporters in the small intestine and kidney.
32 Key words: broiler, gene expression, *myo*-inositol, phytase, phytate

33 **Introduction**

34 Data evaluating the efficacy of phytase in poultry nutrition, to liberate phytate-bound
35 phosphorus is readily available and spans a period of more than 50 years (Nelson, 1967;
36 Dersjant-Li et al., 2015). Recent interest in supplementing poultry diets with higher doses of
37 phytase, sometimes referred to as “superdoses” of phytase, has led to further understanding of
38 phytate hydrolysis and reported benefits in feed conversion (Walk et al., 2013, 2014). These
39 benefits are thought to be predominantly associated with the near complete destruction of
40 phytate (iP6) and lower phytate esters (iP5, iP4, iP3) in the proximal gastrointestinal tract,
41 alleviation of their antinutritional properties (Bedford and Walk, 2016), and the provision of
42 *myo*-inositol (Walk et al., 2014; Cowieson et al., 2015; Lee and Bedford, 2016).

43 *Myo*-inositol is considered an essential constituent of cellular phosphoinositides and is
44 involved in many cellular functions, such as insulin sensitivity, lipid metabolism, and cell
45 survival, structure and growth (Huber, 2016). *Myo*-inositol can be synthesised in the body
46 from glucose, released from cellular phospholipids, and absorbed in the intestinal tract from
47 the diet (Huber, 2016). Free *myo*-inositol can be actively transported with high efficiency via
48 three co-transport systems, two are sodium dependent (SMIT1 or SLC5A3 and SMIT2 or
49 SLC5A11) and one is proton dependent (HMIT or SLC2A13; Aouameur et al., 2007). Using
50 rabbits and rats, previous studies have demonstrated that the expression of each cotransport
51 system is variable between the tissues; SMIT1 is primarily expressed in the brain and renal
52 medulla, SMIT2 is expressed in the brain, intestine, and renal cortex and HMIT is
53 predominantly expressed in the brain (Aouameur et al., 2007; Huber, 2016) with lower levels
54 found in white and brown adipose tissues and the kidney (Mueckler and Thorens, 2014).

55 The location and expression of these cotransport systems in the various tissues may
56 indicate the importance of *myo*-inositol on cellular metabolism and function. Evaluation of
57 the expression of *myo*-inositol cotransport systems in tissues may help to further elucidate the

58 beneficial effects of *myo*-inositol provision through phytate destruction from superdoses of
59 phytase. Therefore, the objective of this trial was to determine the influence of superdoses of
60 phytase on broiler performance, mineral digestibility, specifically Ca, P, Na and K, the
61 concentration of iP6, iP5, iP4, iP3, iP2, and *myo*-inositol in the gizzard and ileum, and the
62 expression of the *myo*-inositol cotransporters in the kidney, liver and small intestine in 21-day
63 old broilers.

64 **Materials and Methods**

65 All animal care procedures used in this experiment were approved by the Scotland's
66 Rural College Animal Experiment Committee (SRUC) before initiation of the experiment.

67 *Animals and Management Practices*

68 Two-hundred and forty male Ross 308 commercial broiler chicks were obtained and
69 allocated to four dietary treatments in a randomized complete block design with six chicks
70 per cage and 10 replicate cages per treatment. Birds were housed at the SRUC poultry farm in
71 thermostatically-controlled brooder battery cages with raised-wire floors with a lighting
72 program of 23L:1D from hatch to day 7 and 14L:10D for the remainder of the 21-day trial.
73 Temperature in the battery cages was maintained at 32°C for the first day of the study and
74 decreased to 21°C by day 21.

75 *Experimental Diets*

76 Chicks were fed one of four dietary treatments that consisted of a low Ca and avP
77 basal diet supplemented with 0, 500, 1,500 or 4,500 FTU/kg of phytase (Table 1). The
78 phytase was a third generation microbial phytase (Quantum Blue, AB Vista, Marlborough,
79 Wiltshire, UK) with an expected activity of 5,000 FTU/g. All diets were formulated to meet
80 Ross 308 nutrient recommendations, with the exception of Ca and avP, which were reduced
81 by 0.16 and 0.15%, respectively (Table 1). Titanium dioxide was included in all diets at
82 0.5% as an indigestible marker to permit calculation of nutrient digestibility by the index

83 method. Access to feed and water was provided *ad libitum* throughout the 21-d feeding
84 period. Feed was fed in mash form via a feed trough and water was provided via a nipple and
85 cup drinker.

86 ***Measurements***

87 Chicks were weighed and randomly allotted such that average initial group weights
88 were distributed similarly across dietary treatments. Birds were monitored daily for
89 morbidity and mortality throughout the study. Dead or culled birds were recorded and these
90 values were used to adjust FI and FCR according to the number of bird days. At the end of
91 the 21-day feeding period, all birds and feeders were weighed to determine BWG, FI, and
92 calculate FCR.

93 ***Collection and Analyses***

94 On day 21, four birds per cage were euthanized by injection of pentobarbital and
95 gizzard and ileal digesta were collected by gently flushing the entire gizzard contents and the
96 terminal ileum (30 cm proximal to the ileo-cecal junction) with deionized water. The digesta
97 samples were pooled per section per cage and immediately frozen (-20°C) for later analysis.
98 Frozen gizzard and ileal digesta samples were lyophilized and ground using a 1 mm screen
99 prior to mineral and phytate ester analyses.

100 Quantification of inositol phosphates in gizzard and ileal digesta samples were
101 determined with a modified method from Kwanyuen and Burton (2005) using high-
102 performance liquid chromatography. Freeze dried samples were extracted with 10 mL of 0.5
103 M HCl for 1 h at 20°C by ultrasonication. The extracts were then centrifuged for 10 minutes
104 at $2,200 \times g$, and 5 mL of the supernatant was evaporated to dryness in a vacuum centrifuge.
105 The samples were then re-dissolved in 1 mL of distilled, deionized water by ultrasonication
106 for 1 h at 20°C and centrifuged for 15 minutes at $18,000 \times g$. The resulting supernatant was
107 filtered through a 13-mm syringe filter with a $0.45 \mu\text{m}$ membrane (GH Polypro Acrodisc[®],

108 Pall Corporation, Ann Arbor, MI) and placed in a 30 kDa centrifugal filter (Microcon[®]
109 Ultracel YM-30, Millipore Corporation, Bedford, MA) and finally centrifuged for 30 minutes
110 at $9,000 \times g$. The samples were then analysed for inositol phosphate moieties (iP2–iP6) using
111 a standard HPLC analytical column (4×250 mm CarboPac PA1 column, Thermo Scientific,
112 Sunnyvale, CA). Phytic acid dodecasodium salt hydrate (Sigma-Aldrich, St. Louis, MO) was
113 used as the standard for both iP6 and the lower iP esters to calculate the ratio between peak
114 area and concentration of iP6 and lower esters in nmol/g in the isolated digesta fractions.

115 Titanium dioxide concentrations of diet and ileal digesta were determined following
116 the procedures of Short et al. (1996). Duplicate samples were weighed into crucibles, dried at
117 105°C for 24 h, and subsequently ashed at 550°C for 24 h. The ashed samples were then
118 dissolved in 7.4 M sulfuric acid. Hydrogen peroxide (30% vol./vol.) was subsequently added
119 to produce a yellow color with an intensity proportional to the titanium dioxide concentration
120 in each sample. Duplicate aliquots of these sample solutions were analyzed using a UV
121 spectrophotometer by measuring the absorbance at 410 nm. Calcium, total P, Na and K were
122 analysed in the diet and ileal digesta samples using Inductively Coupled Plasma – Optical
123 Emission Spectroscopy (AOAC Method 990.08; AOAC, 2006) following digestion, in turn,
124 in concentrated HNO_3 and HCl . Apparent nutrient digestibility (AND, %) was calculated
125 according to the following equation: $\text{AND} = [1 - [(M_i / M_o) \times (X_o / X_i)] * 100,$

126 where M_i = concentration of TiO_2 (marker) of the diet sample,

127 M_o = concentration of TiO_2 (marker) of the ileal digesta,

128 X_o = nutrient concentration of the ileal digesta sample,

129 X_i = nutrient concentration of the diet sample.

130 The remaining 2 birds per cage were euthanized by a lethal injection of pentobarbital to
131 permit collection of tissue samples. An incision was made below the sternum to expose the
132 abdominal cavity as previously described (Olukosi and Dono, 2014). The entire liver and

133 kidney and sections of the jejunum and ileum were collected from each bird, stored in
134 RNAlater and frozen until PCR analyses.

135 The genes analysed in the liver and kidney were sodium/glucose cotransporter 11
136 (SLC5A11 or SMI2); sodium *myo*-inositol cotransporter (SLC5A3 or SMI1) and H⁺/*myo*-
137 inositol transporter (SLC2A13 or HMI). The genes analysed in the intestine were the three
138 listed previously as well as intestinal alkaline phosphatase (ALPI).

139 RNA were extracted from the tissues and total RNA (5 µl) was reverse-transcribed
140 onto cDNA using 20µl RT premix (PrimerDesign, Southampton, UK). The reaction was
141 performed at 55°C for 20 min and 72°C for 10 min. The *Gallus gallus* gene-specific primers
142 for all the genes of interest (Table 2) were designed by PrimerDesign (Southampton, UK).

143 Quantitative Real-Time PCR was performed using Stratagene Mx3005p (Agilent
144 Techonologies, UK). 1µl of each primer/probe mix was combined with 10µl Precision 2×
145 Mastermix and 4µl PCR water (all from PrimerDesign, Southampton, UK). 5µl diluted
146 cDNA was used in each reaction. All PCR were performed in duplicate in Stratagene PCR
147 plates (Agilent Techonologies, UK) under the following conditions: 95°C for 10 min, 40
148 cycles of 95°C for 15 s and 60°C for 1 min. Relative target gene expression level was
149 determined by the comparative cycle threshold (C_T) method (Livak and Schmittgen, 2001).
150 Glyceraldehyde-3-phosphate dehydrogenase gene (**GAPDH**) was used to normalize
151 variations in the amount of mRNA for the target genes. The ΔC_T value was calculated as the
152 difference between the C_T value of each GAPDH and the average C_T value for GAPDH, this
153 value was used to calculate GAPDH fold (i.e. ΔC_T^{1.97}). The same mathematical treatment was
154 done for the C_T value of the target genes and these values were normalized against the value
155 for GAPDH.

156 ***Statistical Analyses***

157 Cage served as the experimental unit for all parameters. Performance, apparent ileal
158 digestibility and phytate and phytate ester data are presented as least square means per
159 treatment group. Gene expression data are presented as the relative fold change when
160 compared to the housekeeping gene, GAPDH. All data were analysed as analysis of variance
161 using the fit model platform in JMP Pro v 13.0 (SAS Institute, Cary, NC). The model
162 included phytase and means were separated using linear and quadratic orthogonal polynomial
163 contrasts. Statistical significance was considered when $P \leq 0.05$ and trends discussed at $P \leq$
164 0.10.

165 **Results**

166 Phytase activity recovered in the experimental diets was higher than expected at < 50,
167 907, 2,050, and 6,120 FTU/kg for 0, 500, 1,500 and 4,500 FTU/kg, respectively. Overall
168 mortality was 5%. Analysed total P, Ca, Na and CP are presented in Table 1 and were within
169 the expected levels for all the diets. Overall feed intake or feed conversion ratio were not
170 influenced by phytase dose (Table 3). Body weight gain from hatch to 21-days post-hatch
171 increased (linear, $P < 0.05$) as phytase dose increased from 0 to 4,500 FTU/kg (Table 3).

172 Apparent ileal digestibility of dry matter (linear, $P < 0.05$) and Ca (quadratic, $P <$
173 0.05) decreased and P (quadratic, $P < 0.05$) and Na (quadratic, $P < 0.05$) increased as phytase
174 dose increased from 0 to 4,500 FTU/kg (Table 4). Increasing phytase dose from 0 to 4,500
175 FTU/kg decreased (quadratic, $P < 0.05$) the concentration of iP6 and iP5 in the gizzard
176 digesta (Table 5). The concentration of iP4, iP3 and iP2 in the gizzard digesta increased and
177 then decreased (all quadratic, $P < 0.05$) as phytase supplementation in the diet increased from
178 0 to 4,500 FTU/kg (Table 5). Inositol concentration increased (linear, $P < 0.05$) in the
179 gizzard digesta as phytase supplementation increased in the diet (Table 5). In the ileal
180 digesta, the concentration of iP6 (linear, $P < 0.05$) decreased and iP5 (quadratic, $P < 0.05$)
181 and iP4 (quadratic, $P < 0.05$) increased and then decreased as phytase dose increased in the

182 diets (Table 6). In contrast to the other phytate esters, the concentration of iP3 (linear, $P <$
183 0.05) and inositol (quadratic, $P < 0.05$) increased as phytase dose in the diet increased to
184 4,500 FTU/kg (Table 6). There was no effect of phytase dose on the concentration of iP2 in
185 the ileal digesta.

186 The relative changes in the gene expression of inositol transporters and intestinal
187 alkaline phosphatase in the jejunum and ileum are presented in Table 7. In the jejunum,
188 increasing phytase dose from 0 to 4,500 FTU/kg up-regulated the relative expression of
189 SLC5A11 (quadratic, $P < 0.05$), tended to up-regulate the relative expression of SLC5A3
190 (quadratic, $P = 0.10$), and there was a tendency ($P < 0.10$) for phytase to up-regulate the
191 relative expression of SLC2A13. There was no effect of phytase dose on the relative
192 expression of iALP in the jejunum. In the ileum, the effect of phytase dose approached
193 significance ($P < 0.06$) towards an up-regulation of the relative expression of SLCA13
194 (linear, $P < 0.05$) and significantly increased the expression of iALP (linear, $P < 0.05$). There
195 was no effect of phytase dose on the relative expression of SLC5A11 or SLC5A3 in the
196 ileum. The effect of phytase dose on gene expression of *myo*-inositol transporters in the liver
197 and kidney were not significant (Table 8).

198 **Discussion**

199 Growth performance of broilers at the conclusion of the trial was 30-39% below Ross
200 308 standards (Ross 308 Broiler Performance Objectives, 2012) and this may be associated
201 with the use of mash diets (Kilburn and Edwards, 2001). Body weight gain and P
202 digestibility increased as phytase supplementation increased and this has been previously
203 reported in low avP diets supplemented with 0 to 12,500 FTU/kg (Karadas et al., 2010) or 0
204 to 24,000 FTU/kg (Cowieson et al., 2006) of phytase indicating further benefits in nutrient
205 digestibility and growth are attainable with higher doses of phytase.

206 Contradictory to previously published research (Walk et al., 2013, 2014), there was no
207 significant effect of phytase dose on FCR in the current trial. Numeric improvements in FCR
208 were noted however, with the highest dose of phytase improving feed efficiency by
209 approximately 14%. Mechanisms by which high doses of phytase elicit beneficial effects on
210 performance are proposed to be related to 1) destruction of the anti-nutritive effects of
211 phytate with generation of more soluble lower phytate esters and 2) generation of *myo*-
212 inositol (Cowieson et al., 2011). Phytate, phytate ester, and inositol concentrations in the
213 gizzard and ileal digesta in the current experiment would partially support the above
214 proposed mechanisms of superdosing. For example, in the gizzard and ileal digesta the
215 concentration of iP6 decreased and the concentration of iP5 and iP4 increased and then
216 decreased, while iP3 and *myo*-inositol concentration increased as phytase supplementation
217 increased in the diet and this has been previously reported (Walk et al., 2014; Beeson et al.,
218 2017). Using *in vitro* models, other authors have reported that phytate, as well as the lower
219 phytate esters, have the capacity to bind minerals and to interfere with pepsin activity,
220 particularly as pH increases, as summarised by Bedford and Walk (2016). While phytate is
221 considered a more potent anti-nutrient than the lower esters, the anti-nutritive effects of these
222 lower esters on minerals (Xu et al., 1992) and pepsin (Yu et al., 2012) requires further
223 consideration, and continued reduction of these phytate esters with high doses of phytase may
224 be a factor contributing to the increase in BWG and numeric improvements in FCR.

225 In addition, the continued destruction of phytate and the lower phytate esters as
226 phytase dose increased also resulted in significant increases in *myo*-inositol in the gizzard and
227 ileal digesta. *Myo*-inositol is an important component of cellular phospholipids and is
228 involved in many cellular functions including survival, structure and signalling (Huber,
229 2016). Previous authors have loosely correlated an increase in *myo*-inositol concentrations in
230 the gizzard with significant improvements in FCR (Walk et al., 2014). Cowieson et al.

231 (2013) reported supplementation of broiler diets with 0.15% *myo*-inositol resulted in
232 significant improvements in FCR of 42-day old broilers. Others have also reported
233 significant increases in plasma *myo*-inositol as phytase supplementation increased in the diet
234 (Cowieson et al., 2015; Laird, 2016). Therefore, it is likely one of the beneficial effects of
235 feeding high doses of phytase would be the provision of *myo*-inositol through phytate and
236 phytate ester destruction.

237 Free *myo*-inositol in the gastrointestinal tract is absorbed with great efficiency, 99.8%
238 (Holub, 1986; Croze and Soulage, 2013) by an active, Na-dependent process. Sodium is
239 transported across the brush border together with *myo*-inositol via SLC5A11 (SMIT2) at a
240 ratio of 2 Na to 1 *myo*-inositol (Huber, 2016). In the current trial, the expression of
241 SLC5A11 was up-regulated in the jejunum and the apparent ileal Na digestibility was
242 significantly increased as phytase supplementation increased in the diet. In addition, at least
243 in the jejunum, there was also a tendency toward an up-regulation of both SLC5A3 (SMIT1)
244 and SLC2A13 (HMIT) as dietary phytase increased from 0 to 4500 FTU/kg, but there was no
245 effect on the gene expression of iALP. In contrast, in the ileum there was no effect of
246 phytase on SLC5A11 (SMIT2) or SLC5A3 (SMIT1) and a tendency for a linear increase in
247 SLC2A13 (HMIT) with a significant increase in iALP expression. These results are
248 interesting, especially when considering previous authors reported the expression of SLC5A3
249 (SMIT1) and SLC2A13 (HMIT) are most noted in the brain and/or kidney with SMIT2
250 predominantly found in the small intestine (Aouameur et al., 2007; Mueckler and Thorens,
251 2013; Huber, 2016). However, species differences exist in *myo*-inositol transporter
252 expression in the tissues, with SMIT2 being expressed in high concentration in the kidney of
253 both rats and rabbits, but barely detectable in the small intestine of rabbits (Aouameur et al.,
254 2007).

255 In the current experiment, the expression of *myo*-inositol transporters was not
256 measured in the brain and more work is needed to confirm the effects reported in herein,
257 particularly in poultry. Regardless, a few interesting points can be discussed based on the
258 gene expression data, specifically:

259 1) *Myo*-inositol appears to be actively transported in the small intestine and
260 transporter expression is influenced by *myo*-inositol concentration, with an up-regulation of
261 the gene expression of SMIT2 or HMIT in the jejunum and ileum as phytase dose and
262 production of *myo*-inositol increased. *Myo*-inositol uptake in the brush border vesicles of rats
263 has been previously reported through SMIT2 with no evidence of uptake from HMIT or
264 SMIT1 (Aouameur et al., 2007). However, as previously mentioned, these same authors
265 reported barely any SMIT2 detection in the rabbit intestine, indicating species differences
266 exist and these results need to be confirmed in subsequent trials. Regardless, it would appear
267 there is an effect of *myo*-inositol concentration in the intestinal lumen on the up-regulation of
268 transporters in the jejunum of poultry.

269 2) In the ileum however, only HMIT expression was up-regulated as phytase dose
270 increased. This could also be related to the concentration of *myo*-inositol present in the ileum
271 but also due to the reduction of Na concentration (as depicted by an increase in Na
272 digestibility) and the concentration and type of soluble lower phytate esters present in the
273 ileal lumen, which subsequently resulted in an up-regulation of intestinal alkaline
274 phosphatase (Schlemmer et al., 2009); all of which resulted in an increase in HMIT, the
275 proton dependent *myo*-inositol transporter. Previous authors have reported phytase specific
276 activity along the intestinal brush border of broilers and layers, with intestinal phytase
277 activity decreasing from the duodenum to the ileum (Maenz and Classen, 1998). These
278 results may be contradictory to the current trial; however specific phytase activity was not
279 evaluated and effects cannot be compared directly. Furthermore, the iALP expression in the

280 jejunum and the ileum of birds fed 0 FTU phytase/ kg diet was 0.949 vs 0.932, respectively
281 and phytase had a significant effect in the ileum, suggesting the response to HMIT and iALP
282 in the ileum was associated with lower phytate esters and the production of inositol by iALP.

283 Interestingly, even by the terminal ileum the concentration of inositol was remarkably
284 high (53% of the total), indicating there is a rate-limiting step in inositol absorption within the
285 gastrointestinal tract. This is contradictory to previous estimates of free *myo*-inositol
286 absorption in the human small intestine at around 99.8% (Holub, 1986; Croze and Soulage,
287 2013). However, the differences may be dependent on the availability of Na and H⁺ and the
288 location in the GIT. For example, previous authors reported phytase supplementation
289 significantly increased pH in the distal ileum from 6.56 in birds fed 0 FTU/kg phytase to 6.99
290 in birds fed 5,000 FTU/kg phytase (Walk et al., 2012). Taking the anti-log of these pH
291 values indicates an almost 40% reduction in H⁺ ion concentration (2.754E-07 vs 1.023E-07)
292 in the ileum of broilers fed 5,000 FTU/kg of phytase compared with that of broilers fed 0
293 FTU/kg phytase. In effect, this means that while phytase supplementation increases *myo*-
294 inositol concentration, it also creates a rate-limiting step in *myo*-inositol uptake by the ileum
295 by increasing Na digestibility and reducing H⁺ ions which are needed for co-transport of *myo*-
296 inositol. The lack of an effect of phytase dose on SMIT1 or SMIT2 support this as they are
297 both Na dependent co-transporters.

298 3) Finally, notable is the non-significant effect of phytase dose on *myo*-inositol
299 transporter gene expression in the kidney and liver. Both the liver and kidney play important
300 roles in *myo*-inositol metabolism and *de novo* synthesis and the kidney is the main site of
301 *myo*-inositol excretion (Holub, 1986; Lahjouji et al., 2007; Croze and Soulage, 2013). The
302 lack of an effect of phytase dose may be indicative of a reduced need for endogenous
303 synthesis or excretion of *myo*-inositol due to the provision of dietary *myo*-inositol. These

304 results require further evaluation but may be indicative of the pathways and the regulation of
305 *myo*-inositol provided from phytate destruction in the diet.

306 In conclusion, supplementation of broiler diets with phytase up to 4,500 FTU/kg
307 significantly increased weight gain and resulted in nearly complete phytate and phytate ester
308 destruction and the significant increases in *myo*-inositol. This influenced and up-regulated
309 the gene expression Na^+ of H^+ -dependent *myo*-inositol transporters within the jejunum and
310 the ileum, respectively. These results may indicate *myo*-inositol is predominantly taken up in
311 the broiler proximal small intestine via a Na^+ -dependent transporter, whereas in the distal
312 intestine phytate esters created from phytate destruction may up-regulate the expression of
313 alkaline phosphatase, which in turn yields *myo*-inositol and increases the expression of the
314 proton dependent *myo*-inositol transporter, HMIT. Data from the liver and kidney need
315 further evaluation but may indicate complex pathways in regards to regulation of *myo*-
316 inositol in tissues beyond the intestine.

317 **References**

- 318 AOAC. 2006. Official methods of analysis. 18th ed. AOAC Int., Arlington, VA.
- 319 Aouameur, R., S. Da Cal, P. Bissonnette, M. J. Coady, and J.-Y. Lapointe. 2007. SMIT2
320 mediates all *myo*-inositol uptake in apical membranes of rat small intestine. Am. J.
321 Physiol. Gastrointest. Liver Physiol. 293:G1300-G1307.
- 322 Bedford, M. R. and C. L. Walk. 2016. Reduction of phytate to tetrakisphosphate (IP_4) to
323 triphosphate (IP_3), or perhaps even lower, does not remove its antinutritive properties.
324 Pages 45-52 in Phytate Destruction – Consequences for Precision Animal Nutrition.
325 eds. C. L. Walk, I. Kuhn, H. H. Stein, M. T. Kidd, and M. Rodehutschord, Wageningen
326 Academic Publishers, the Netherlands.

327 Beeson, L. A., C. L. Walk, M. R. Bedford, and O. A. Olukosi. 2017. Hydrolysis of phytate to
328 its lower esters can influence the growth performance and nutrient utilization of
329 broilers with regular or super doses of phytase. *Poult. Sci.* doi: 10.3382/ps/pex012.

330 Bradbury, E. J., S. J. Wilkinson, G. M. Cronin, C. L. Walk, and A. J. Cowieson. 2016. Effects
331 of phytase, calcium source, calcium concentration and particle size on broiler
332 performance, nutrient digestibility and skeletal integrity. *Anim. Prod. Sci.*
333 doi.org/10.1071/AN16175.

334 Cowieson, A.J., R. Aureli, P. Guggenhuhl, and F. Fru-Nji. 2015. Possible involvement of
335 *myo*-inositol in the physiological response of broilers to high doses of microbial
336 phytase. *Anim. Prod. Sci.* 55:710-719.

337 Cowieson, A.J., A. Ptak, P. Mackowiak, M. Sassek, E. Pruszyńska-Oszmalek, K. Zyla, S.
338 Swiatkiewicz, S. Kaczmark, and D. Jozefiak. 2013. The effect of microbial phytase
339 and *myo*-inositol on performance and blood biochemistry of broiler chickens fed
340 wheat/corn-based diets. *Poult. Sci.* 92:2124-2134.

341 Cowieson, A.J., P. Wilcock, and M. R. Bedford. 2011. Superdosing effects of phytase in
342 poultry and other monogastrics. *World's Poult. Sci. J.* 67:225-235.

343 Cowieson, A.J., T. Acomavic, and M. R. Bedford. 2006. Supplementation of corn-soy-based
344 diets with an *Escherichia coli*-derived phytase: Effects on broiler chick performance
345 and the digestibility of amino acids and metabolizability of minerals and energy.
346 *Poult. Sci.* 85:1389-1397.

347 Croze, M. I. and C. O. Soulage. 2013. Potential role and therapeutic interests of *myo*-inositol
348 in metabolic diseases. *Biochim.* 95:1811-1827.

349 Dersjant-Li, Y., A. Awati, H. Schulze, and G. Partridge. 2015. Phytase in non-ruminant
350 animal nutrition: a critical review on phytase activities in the gastrointestinal tract and
351 influencing factors. *J. Sci. Food Agric.* 95:878-896.

352 Holub, B.J. 1986. Metabolism and function of *myo*-inositol and inositol phospholipids.
353 Annual Rev. Nutr. 6:563-597.

354 Huber, K. 2016. Cellular *myo*-inositol metabolism. Pages 53-60 in Phytate Destruction –
355 Consequences for Precision Animal Nutrition. eds. C. L. Walk, I. Kuhn, H. H. Stein,
356 M. T. Kidd, and M. Rodehutschord, Wageningen Academic Publishers, the
357 Netherlands.

358 Lahjouji, K., R. Aouameur, P. Bissonnette, M. J. Coady, D. G. Bichet, and J.-Y. Lapointe.
359 2007. Expression and functionality of the Na⁺/*myo*-inositol cotransporter SMIT2 in
360 rabbit kidney. Biochim. Biophys. Acta. 1768:1154-1159.

361 Karadas, F., V. Pirgozliev, A. C. Pappas, T. Acamovic, and M. R. Bedford. 2010. Effects of
362 different dietary phytase activities on the concentration of antioxidants in the liver of
363 growing broilers. J. Anim. Physiol. Anim. Nutr. 94:519-526.

364 Kilburn, J. and H. M. Edwards Jr. 2001. The response of broilers to the feeding of mash or
365 pelleted diets containing maize of varying particle sizes. Br. Poult. Sci. 42:484-492.

366 Kwanyuen, P. and J. W. Burton. 2005. A simple and rapid procedure for phytate
367 determination in soybean and soybean products. J. Am. Oil Chem. Soc. 82:81-85.

368 Laird, S. 2016. The effects of super-dosing phytase in the growing pig. PhD Diss. University
369 of Leeds, UK.

370 Lee, S. A. and M. R. Bedford. 2016. Inositol – An effective growth promotor? World's Poult.
371 Sci. J. 72:743-760.

372 Livak, K. J. and T. D. Schmittgen. 2001. Analysis of relative gene expression data using real-
373 time quantitative PCR and the $2^{-\Delta\Delta C(T)}$. Methods. 25:402-408.

374 Maenz, D. D. and H. L. Classen. 1998. Phytase activity in the small intestinal brush border
375 membrane of the chicken. Poult. Sci. 77:557-563.

376 Mueckler, M. and B. Thorens. 2014. The SLC2 (GLUT) family of membrane transporters.
377 Mol. Aspects. Med. 34:121-138.

378 Nelson, T. S. 1967. The utilization of phytate phosphorus by poultry – a review. *Poult. Sci.*
379 46:862-71.

380 Olukosi, O. A. and N. D. Dono. 2014. Modification of digesta pH and intestinal morphology
381 with the use of benzoic acid or phytobiotics and the effects on broiler growth
382 performance and nutrient utilization. *J. Anim. Sci.* 92:3945-3953.

383 Schlemmer, U., W. Frolich, R. M. Prieto, and F. Grases. 2009. Phytate in foods and
384 significance for humans: Food sources, intake, processing, bioavailability, protective
385 role and analysis. *Mol. Nutr. Food Res.* 53:S330-S375.

386 Short, F. J., P. Gorton, J. Wiseman, and K. N. Boorman. 1996. Determination of titanium
387 dioxide added as an inert marker in chicken digestibility studies. *Anim. Feed Sci.*
388 *Technol.* 59:215-221.

389 Walk, C. L., T. T. Santos, and M. R. Bedford. 2014. Influence of superdoses of a novel
390 microbial phytase on growth performance, tibia ash, and gizzard phytate and inositol
391 in young broilers. *Poult. Sci.* 93:1172-1177.

392 Walk, C. L., M. R. Bedford, T. T. Santos, D. Paiva, J. R. Bradley, H. Wlodecki, C. Honaker,
393 and A. P. McElroy. 2013. Extra-phosphoric effects of superdoses of a novel microbial
394 phytase. *Poult. Sci.* 92:719-725.

395 Walk, C. L., M. R. Bedford, and A. P. McElroy. 2012. Influence of limestone and phytase on
396 broiler performance, gastrointestinal pH, and apparent ileal nutrient digestibility.
397 *Poult. Sci.* 91:1371-1378.

398 Xu, P., J. Price, A. Wise, and P. J. Aggett. 1992. Interaction of inositol phosphates with
399 calcium, zinc, and histadine. *J. Inorg. Biochem.* 47:119-130.

400 Yu, S., A. Cowieson, C. Gilbert, P. Plumstead, and S. Dalgaard. 2012. Interactions of
401 phytate and *myo*-inositol phosphate esters (IP₁₋₅) including IP₅ isomers with dietary
402 protein and iron and inhibition of protein. J. Anim. Sci. 90:1824-1832.

403 **Table 1.** Formulated and analysed nutrient composition of the
 404 experimental diets (% , as fed)

Ingredient	Basal diet
Wheat	61.15
Soybean meal	30.04
Soya oil	4.83
Salt	0.32
Limestone	0.92
Dicalcium phosphate	1.05
Sodium bicarbonate	0.15
Lysine HCl	0.14
DL-Methionine	0.24
Threonine	0.07
Vitamin and trace minerals premix ¹	0.50
Inert or phytase	0.09
TiO marker	0.50
Total	100.00
Formulated nutrient composition	
Crude protein	21.50
ME, kcal/kg	3100.00
Dry matter	87.30
Ca	0.80
P	0.55
Available P	0.30
Phytate P	0.23
Digestible Met + Cys	0.84
Digestible Lys	1.10
Digestible Thr	0.73
Digestible Val	0.84
Sodium	0.18
Chloride	0.28
Analyzed nutrient composition	
Crude protein	22.2
Calcium	0.83
Total phosphorus	0.50
Sodium	0.18

405 ¹Supplied the following per kilogram of diet: vitamin A, 5,484 IU;
 406 vitamin D₃, 2,643 ICU; vitamin E, 11 IU; menadione sodium
 407 bisulfite, 4.38 mg; riboflavin, 5.49 mg; d-pantothenic acid, 11 mg;
 408 niacin, 44.1 mg; choline chloride, 771 mg; vitamin B₁₂, 13.2 µg;
 409 biotin, 55.2 µg; thiamine mononitrate, 2.2 mg; folic acid, 990 µg;
 410 pyridoxine hydrochloride, 3.3 mg; I, 1.11 mg; Mn, 66.06 mg; Cu,
 411 4.44 mg; Fe, 44.1 mg; Zn, 44.1 mg; Se, 250 µg.

412 **Table 2.** GenBank accession number, sequences of forward and reverse primers and
 413 fragments sizes used for real-time PCR

Target	Accession number	Primer sequence	Size (bp)
SLC5A11	XM_01529447	F: 5'-ATGACCATCCCGTCCCTGT-3' R: 5'-CCTTGGCGTGTGAGAGGTT-3'	88
SLC5A3	000282	F: 5'-GGCTGTACTTCGTGCTTGTAAT-3' R: 5'-CCTGCCAAGAAGTAGCCACT-3'	88
SLC2A13	XM_00123293	F: 5'-CATCTATGACAGTGCCTGTGTAC-3' R: 5'- CTCCAGTGATGAACAGAGTGTTAAT-3'	93
ALPI	XM_01529148	F: 5'-AGTCACTTCTCCCTGACTCTG-3' R: 5'-GCCTTCTGTGTCCATGAAGC-3'	84
GAPDH	NM_204305	F: 5'-CCCCA CTCCAATTTCTTC-3' R: 5'- CAGATGGTGAACACTTTTATTGATG-3'	105

- 414 SLC5A11 = SMIT2 (sodium/glucose cotransporter 11).
 415 SLC5A3 = SMIT1 (sodium/*myo*-inositol cotransporter).
 416 SLC2A13 = HMIT (H⁺/*myo*-inositol transporter).
 417 ALPI = intestinal alkaline phosphatase.
 418 GAPDH, glyceraldehyde 3-phosphate dehydrogenase.

419 **Table 3.** Growth performance of broilers fed phytase from hatch to 21-days
 420 post-hatch

Phytase, FTU/kg	Feed intake, g	Weight gain, g	FCR, g:g
0	938.0	581.6	1.635
500	887.3	603.0	1.500
1500	978.3	641.3	1.552
4500	949.0	675.1	1.410
SEM	30.6	22.6	0.09
P-values			
Phytase	0.483	0.012	0.351
Linear	0.251	0.003	0.151
Quadratic	0.729	0.783	0.969

421 Means are based on 6 birds per pen and 10 replicate pens per diet.

422 **Table 4.** Apparent ileal nutrient digestibility of broilers fed phytase from hatch to 21-days
 423 post-hatch

Phytase, FTU/kg	Dry matter, %	Ca, %	P, %	K, %	Na, %	Na, g/kg DMI ¹
0	73.60	69.87	69.41	88.48	-15.98	0.25
500	71.24	56.82	66.95	86.15	-27.66	0.25
1500	68.92	56.26	73.95	86.08	-19.30	0.24
4500	70.24	59.43	81.42	85.89	-0.20	0.21
SEM	0.97	1.79	1.83	1.08	7.31	0.02
P-values						
Phytase	0.005	< 0.001	< 0.001	0.196	0.038	0.314
Linear	0.006	< 0.001	< 0.001	0.136	0.091	0.191
Quadratic	0.066	< 0.001	0.010	0.329	0.043	0.423

424 Means are based on 4 birds per pen and 10 replicate pens per diet.

425 **Table 5.** Phytate, phytate esters and inositol concentration (umol/g DM) in the gizzard digesta of broilers fed phytase from hatch to 21-days post
 426 hatch

Phytase, FTU/kg	Inositol	iP2 ¹	iP3 ²	iP4 ³	iP5 ⁴	iP6 ⁵	∑iP6-iP2 ⁶
0	0.936	1.448	0.319	0.920	1.918	4.296	8.902
500	1.353	1.807	0.753	1.845	0.683	0.463	5.290
1500	1.542	1.761	0.765	0.610	0.030	0.063	3.228
4500	2.305	1.635	0.635	0.386	0.014	0.050	2.719
SEM	0.090	0.072	0.066	0.143	0.159	0.227	0.298
P-values							
Phytase	< 0.001	0.003	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Linear	< 0.001	0.161	0.004	< 0.001	< 0.001	< 0.001	< 0.001
Quadratic	0.062	0.002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

427 Means are based on 4 birds per pen and 10 replicate pens per diet.

428 ¹ Inositol bisphosphate.

429 ² Inositol triphosphate.

430 ³ Inositol tetraphosphate.

431 ⁴ Inositol pentaphosphate.

432 ⁵ Inositol hexakisphosphate (phytate, phytic acid).

433 ⁶ Sum of iP2 to iP6 concentration.

434 **Table 6.** Phytate, phytate esters and inositol concentration (umol/g DM) in the ileal digesta of broilers fed phytase from hatch to 21-days post
 435 hatch

Phytase, FTU/kg	Inositol	iP2 ¹	iP3 ²	iP4 ³	iP5 ⁴	iP6 ⁵	∑iP6-iP2 ⁶
0	6.820	7.269	0.231	0.820	2.704	30.325	41.349
500	8.307	7.529	0.499	2.055	4.076	23.519	37.677
1500	11.489	7.040	0.726	2.504	2.933	12.475	25.678
4500	15.594	7.341	0.796	1.553	0.560	2.757	12.927
SEM	0.644	0.345	0.082	0.271	0.322	1.973	2.503
P-values							
Phytase	< 0.001	0.950	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Linear	< 0.001	0.754	< 0.001	0.032	< 0.001	< 0.001	< 0.001
Quadratic	0.050	0.953	0.238	< 0.001	< 0.001	0.466	0.078

436 Means are based on 4 birds per pen and 10 replicate pens per diet.

437 ¹ Inositol bisphosphate.

438 ² Inositol triphosphate.

439 ³ Inositol tetraphosphate.

440 ⁴ Inositol pentaphosphate.

441 ⁵ Inositol hexakisphosphate (phytate, phytic acid).

442 ⁶ Sum of iP2 to iP6 concentration.

443 **Table 7.** Expression of genes in the small intestine mucosa of broilers fed phytase from hatch to 21-days post hatch

Phytase, FTU/kg	Jejunum				Ileum			
	SLC5A11 ¹	SLC5A3 ²	SLC2A13 ³	iALP ⁴	SLC5A11 ¹	SLC5A3 ²	SLC2A13 ³	iALP ⁴
0	0.661	0.923	0.962	0.949	1.218	0.994	0.975	0.932
500	1.147	0.804	0.834	1.041	1.344	0.846	0.837	1.463
1500	3.094	1.455	1.476	1.140	1.096	0.636	0.975	1.036
4500	2.890	1.232	1.331	1.159	1.128	1.139	1.452	2.295
SEM	0.38	0.20	0.17	0.16	0.17	0.11	0.12	0.23
P-values								
Phytase	0.002	0.149	0.090	0.703	0.760	0.263	0.055	0.027
Linear	0.003	0.236	0.314	0.521	0.897	0.206	0.007	0.009
Quadratic	0.017	0.101	0.112	0.703	0.731	0.146	0.965	0.265

444 Means are based on 2 birds per pen and 10 replicate pens per diet.

445 ¹ SLC5A11 = SMIT2 (sodium/glucose cotransporter 11).

446 ² SLC5A3 = SMIT1 (sodium/*myo*-inositol cotransporter).

447 ³ SLC2A13 = HMIT (H⁺/*myo*-inositol transporter).

448 ⁴ iALP = intestinal alkaline phosphatase.

449 **Table 8.** Expression of genes in the kidney and liver of broilers fed phytase from hatch to 21-days
 450 post hatch

Phytase, FTU/kg	Kidney			Liver		
	SLC5A11 ¹	SLC5A3 ²	SLC2A13 ³	SLC5A11 ¹	SLC5A3 ²	SLC2A13 ³
0	0.971	0.936	1.026	0.948	1.116	1.148
500	1.195	0.708	0.887	0.943	1.157	0.826
1500	0.912	0.819	0.870	1.396	0.936	0.967
4500	0.641	0.734	0.744	1.160	0.820	0.924
SEM	0.20	0.09	0.09	0.16	0.13	0.12
P-values						
Phytase	0.410	0.234	0.174	0.247	0.334	0.379
Linear	0.170	0.390	0.044	0.846	0.103	0.481
Quadratic	0.921	0.516	0.565	0.069	0.528	0.443

451 Means are based on 2 birds per pen and 10 replicate pens per diet.

452 ¹ SLC5A11 = SMIT2 (sodium/glucose cotransporter 11).

453 ² SLC5A3 = SMIT1 (sodium/*myo*-inositol cotransporter).

454 ³ SLC2A13 = HMIT (H^+ /*myo*-inositol transporter).