
The role of bioavailable silica in supporting poultry growth and development

Journal:	<i>World's Poultry Science Journal</i>
Manuscript ID	WPSJ-RE-2024-123.R2
Manuscript Type:	Review
Keywords:	feed, minor species, nutrition, supplements, welfare
Species:	broiler, layers

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Summary

Silica is known to be an important essential ultra-trace mineral which does not currently have a recommended level for supplementation in poultry, beyond avoidance of deficiency. The chemistry of silicon dictates its bioavailability, depending on source and concentration, solubility varies widely. This review details the chemistry and biology of silica and the potential mode of action for improving bone health, while also bringing together research from human and other animal fields. The poultry sector has investigated the effect of supplementation with several silicon containing compounds with inconsistent outcomes. This may be due to the large variability in bioavailability of differing silicon containing compounds, so this is also discussed. Finally, the authors consider whether bioavailable silica should have a recommended supplemented level for poultry to maximise performance and skeletal integrity in the future, and if so, should this be of a known bioavailable form.

Keywords: Silica, silicic acid, broiler, nutrition, bone integrity, collagen, mineralization

Introduction

It has been reported that 66 billion broilers are slaughtered every year in the world, with most birds being produced in the United States, China, and Brazil (Phibbs *et al.* 2021). This leading role in global meat supply means the broiler sector is under significant pressure to improve productivity and efficiency to cope with an increasing demand for chicken meat. Rapid growth

and high proportion of edible meat associated with the most resource-efficient strains of poultry has led to an increased risk of lameness, particularly under large-scale farming systems (Mottet and Tempio 2017). Lameness in broilers raises welfare concerns as it is associated with pain (McGeown *et al.* 1999) and restricts the ability of birds to reach food and water (Sanotra *et al.* 2002) which negatively affects growth performance (Gocsik *et al.* 2014) and increases mortality rate (Wideman *et al.* 2012). Currently, genetic selection, adjusting housing conditions, and nutritional interventions are used to prevent lameness or to decrease its negative impact on poultry welfare (Phibbs *et al.* 2021). Both Ca and P nutrition are critical to poultry skeletal integrity and the role of Ca and P in bone mineralisation is extensively reviewed (Li *et al.*, 2017; Matuszewski *et al.*, 2020). However, little consideration has been given to dietary bioavailable silica supplements.

Silicon has been commonly used in animal feeds in the form of hydrated aluminosilicate (zeolite) as an adsorbent of unwanted substances such as plant fungal toxins and excess nitrogen compounds. (Papaioannou *et al.* 2005). However, Silicon is known to be an important essential ultra-trace element which does not currently have a recommended level for supplementation of poultry, beyond avoidance of deficiency (Tran *et al.* 2015). Historically, bioavailable silica has been linked to roles maintaining bone health and connective tissue metabolism. However, analysis of the effect of silica on poultry performance has been inconsistent due to the variability and lack of clarity surrounding the element's bioavailability and mode of action. In view of the frequency of skeletal integrity issues in poultry, this review brings together disparate background knowledge on the chemistry and biology of silica, research performed in the area and considers whether addition of silica to feed is a potential benefit for the industry in the future both in terms of its impact on production efficiency and

bone health. For avoidance of confusion, we define the different forms of silicon containing molecules and materials relevant to the discussion below.

Si: The chemical symbol for the element and the generic term used when the nature of the specific silicon compound is not known.

Si(OH)_4 : Orthosilicic acid (OSA), the fundamental building block used in the formation of silicas and the bioavailable form of silicon together with the anionic form Si(OH)_3^- found at significant levels at pH values above 3 and the dominant species above pH 9. we refer to this as soluble silicon. Alternative names include monosilicic acid, sometimes shortened to MOSA in the literature.

$\text{SiO}_2 \cdot n\text{H}_2\text{O}$ or $\text{SiO}_2 \cdot x(\text{OH})_{2x} \cdot 2\text{H}_2\text{O}$: Amorphous, hydrated, polymerized material found in biogenic silicas including grains. The pK_a of silanol groups on the surface of the material is ca. 6.8 which means that silicas are often negatively charged. Size and form affect solubility.

Polymerization: The mutual condensation of silicic acids to give molecularly coherent units of increasing size.

TMOS, TEOS: Alkoxy silanes; tetramethoxysilane and tetraethoxysilane used as precursors for supersaturated orthosilicic acid solutions.

Silanol: Hydroxyl group bonded to a silicon atom.

Silicate: A chemically specific ion having negative charge (e.g. SiO_3^{2-}), a term also used to describe salts (e.g. sodium silicate, Na_2SiO_3). Silicates have been used to generate solutions containing high levels of monomeric silicon species (SiO_3^{2-}) but are usually highly caustic.

Zeolite: often, but not exclusively, a highly porous hydrated aluminosilicate of alkaline or alkaline earth cations which can be manmade or naturally occurring. Composition and form affect solubility.

Silicon as a mineral

Silicon (Si) is a non-metallic element with an atomic weight of 28 which occurs naturally as oxides or silicates. Si is the most abundant component of minerals, with only 8% of the earth's crust being non-silicate material (Iler 1979). It is not found in its elemental form in nature as it is highly chemically reactive and has a high affinity for oxygen. Silicon is very scarce in the hydrosphere and, its bioavailability is low (Iler 1979). However soluble silicon can be released from stable silicates through biochemical reaction by plants and weathering (Jugdaosingh *et al.* 2008), therefore rendering these minerals bioavailable in water at low concentrations (Birchall 1995). The chemical composition of individual silicates also affects its solubility (Powell *et al.* 2005). Highly condensed silicas (such as fumed silica generated by high temperature processes) are less soluble than hydrated silica generated at lower temperatures; additionally, crystalline silica is less soluble than amorphous (Gunnarsson and Arnórsson 2000). Size and shape play a role in solubility with smaller irregularly shaped particles showing higher solubility than larger, regular shaped particles (Alexander 1957). The presence of metal ions in the silica matrix at trace levels also increases dissolution rates (Dove 1999).

Once in solution, Si from soil minerals forms soluble species by way of hydrolysis, the most stable of which is monomeric silica with formula $\text{Si}(\text{OH})_4$ which is water-soluble with a pK_a of 9.6, however this only remains soluble at a total Si concentration below 2mM (Iler 1979) (Arthur 2008). This means that at physiologically relevant pH values the molecule carries little charge though, as pH increases, the presence of anionic species such as $\text{Si}(\text{OH})_3\text{O}^-$ will increase. Polymerisation which occurs above 2 mM Si reduces solubility leading to lower bioavailability (Jugdaosingh *et al.* 2008). Only the monomer and perhaps very small molecular condensates (dimers) are thought to be bioavailable. Silicon from plant sources mainly

includes species that produce grains such as oats, barley and rice as well as legumes and fruits such as bananas which have higher silicon content as compared to food from animal sources (Henriet *et al.* 2006). It should be noted however that the bioavailability of the element may not correlate with total silicon content (Robberecht *et al.*, 2008; Dejneka and Lukasiak 2003). Thus, the bioavailability of silicon from different sources should always be determined since bioavailability is a measure of potential effectiveness of a nutrient and is determined as the proportion of the material utilized from the total amount of a nutrient provided for normal metabolism in the body (Fairweather-Tait 1999).

Assessment of soluble silicon concentrations

Solution silica concentrations are determined usually by one of two methods. Firstly, by inductively coupled plasma with either optical emission (ICPOES) or mass spectrometric (ICPMS) detection. The plasma generated is not enough in this process to completely ionise the silica present, so the method is unable to distinguish between monomeric true solution and suspended polymeric species in the system. Ultrafiltration is sometimes used to remove suspended particulate (Magnusson *et al.*, 2021) but cannot realistically be used to remove material in the sub 3 nm range with silica particulates of 1nm containing a minimum of 27 Si atoms still potentially present but not bioavailable. Where this distinction between monomeric and polymeric forms needs to be made, for example in measuring 'bioavailable' silicon, a second colorimetric molybdenum complexation method can be employed (Coradin *et al.* 2004). In this method a single monosilicate anion resides in the central cavity of a so-called Keggin structure in which the ion sits tetrahedrally co-ordinated at the centre of a 12 membered molybdic heteropoly acid unit (the silicomolybdic acid (yellow) complex) typically measured in a spectrometer at 400nm. Because the cavity can accommodate a single anion

only the monomer or silicate species that dissociate to the monomer in the molybdate complexation reaction time will be measured. Where higher sensitivity is required the complex can be reduced chemically using mild reducing agents such as stannous chloride, sulphur dioxide or sulphites to the silicomolybdous (blue) complex which has a significantly higher absorbance extinction co-efficient at 810 nm. To assess whether a silicon containing material is bioavailable it is imperative that concentrations of the soluble form under conditions matched to those experienced in the living organism are measured.

The biological role of Silica

Plants and lower organisms including diatoms, dinoflagellates and sponges utilise Si for formation of exoskeletons made of biogenic silica, hydrated SiO_2 (Perry, 2009). They intake monomeric silicic acid from a range of freshwater and saline water environments and process the mineral to generate complex composite mineral:biopolymer structures that provide, as a minimum, structures that support and protect the organism. The organisms are clearly able to process the element at all stages from monomer through to mineral via a wide range of biochemical processing and further, they can control the level of hydration and spatial organisation (Parambath *et al.* 2022).

Orthosilicic acid $[\text{Si}(\text{OH})_4]$ constitutes more than 90% of dissolved silicon and is reported as the primary form absorbed by humans and can be found in body tissues such as the bone, kidney, tendons, aorta and liver (Martin, 2007). However, the majority of Si present in the diet is not in this monomeric form, but condensed into polymers that cannot be absorbed. The chemistry of Si dictates its bio-availability, depending on solubility, and this varies widely with source and form (Martin 2013). Absorbance of monomeric Si within the gastrointestinal tract can be demonstrated due to its penetration of body fluids and tissues, with elevated

concentrations found in bone, and the parenchymal tissues (Carlisle 1984) but the mechanisms involved in absorption, metabolism and excretion are generally poorly understood (Jugdaohsingh 2007). Absorption requires the breakdown of materials ingested into soluble orthosilicic acid which is uncharged and therefore mobility and permeability across the mucosal layer of the intestine is successful. The rate and efficiency of absorption also depend on concentration, as higher concentrations permit polymerisation and reduced permeability (Anderson *et al.* 1998). This makes supplementation with higher Si levels problematic. Development of silica supplements that remain bioavailable has therefore become a focus area for researchers.

An alternative route to maintaining bioavailability of silica has considered the use of monomethylsilanetriol (MMST) in mammalian studies (rats and mice) (Jugdaosingh *et al.*, 2015). The researchers explored the potential for vitamin D combined with soluble silicon supplements and found a positive correlation between serum silicon levels and bone quality was observed for female rats. In contrast, other research on rats using purported silicon chelates (data for presence of silicon in a bioavailable form not provided) formed by mechano reaction between rice husks containing polymerised silica and green tea containing catechins (Bychkov *et al.* 2022) only found small changes in one biochemical marker of mineralisation, alkaline phosphatase (ALP) and no effects on bone formation itself.

Silicon has been established as an essential trace nutrient (Carlisle 1988; Seaborn and Nielsen 1994; Birchall 1995) with these early studies using minimal diets postulating its involvement in early calcification, growth and skeletal development, connective tissue metabolism, wound healing and immune response. Further investigations into the biochemical role of silicon in bone development showed silicon influenced mineralization, trace metals utilization and prevention of aluminium toxicity (Jugdaosingh *et al.* 2008). More recently, it has been

proposed that the role of silicon in bone tissues is in its involvement in the synthesis of osteoblast and extracellular matrix components with a structural function as a crosslink between procollagen molecules in collagen production (Dinjaski *et al.* 2017; Martín-Moldes *et al.* 2018).

The role of Silica in bone formation and calcification

Early studies on both chickens (Carlisle 1972) and rats (Schwarz and Milne 1972) using deprivation diets with silicon added as sodium silicate (a source which provides monomeric silicon but which is highly caustic unless heavily diluted or treated with acid to neutralise) demonstrated that Silicon significantly affects growth and skeletal development. Si deprived chicks had significantly lower weight gain with abnormal skeletal development comprising shorter leg bones of smaller circumference and thinner cortex, as well as easily fractured tibia and femur (Carlisle 1972). Bone development appeared to be affected in both chicks (Carlisle 1972, 1981a) and rats (Schwarz 1973; Seaborn and Nielsen 2002) with both animal types showing reduced calcification and skull deformities. However, it should be noted that the early experiments on animals used purified diets made from purified starch and crystalline amino acid based diets which are likely to be compromised in other aspects nutritionally required to support growth, but the inclusion of silicon in these diets alleviated some of the symptoms and a series of studies by (Elliot and Edwards 1991) using both purified and practical-type diets did not reveal an impact of diet type. From early studies, these bone formation effects also seem to be independent of vitamin D levels (Carlisle 1981b).

Benefits of silicon to bone formation are well documented, particularly to osteoblast cell culture across paired tibial cartilaginous epiphyses, chondrocytes and paired frontal bones of broiler chicks (Carlisle and Suchil 1983, Carlisle and Alpenfels 1984). Support for Si

192 supplementation leads to increased bone mineral density, reduction in bone fragility and
193 promotion of bone resorption (Hott *et al.* 1993). *In vitro* studies on tibias of rats found silicon
194 localized in the active calcification region and was involved in the initiation of mineralization
195 of pre-osseous tissue involving hydroxyapatite (Carlisle 1970) where hydroxyapatite is
196 important in enabling compressional strength in bone to develop (Rath *et al.* 2000).

197 In contrast to the results discussed above where silicon supplementation led to an increase
198 in bone properties, other studies however, have observed that high silicon supplemented rats
199 and turkey had lower bone size and lower strength parameters (maximal load and elasticity)
200 of both femur and tibia bones (Kayongo-Male and Julson 2008). These researchers suggested
201 that an interaction between silicon and minerals such as calcium and magnesium affects
202 mineralization of the bone and thereby the mechanical properties of the bones. These
203 contrasting results could possibly be explained by the difference in the amount of
204 supplemented silicon or the form in which silicon was supplied to the animals. As examples,
205 studies by Carlisle supplemented sodium metasilicate either at 100 or 250 ppm, however
206 (Elliot and Edwards 1991) supplemented chicks with 50, 150 or 250 mg/ kg sodium
207 metasilicate and (Kayongo-Male and Julson 2008) reported high inclusion levels of silicon at
208 500 ppm/ kg in the form of tetraethylorthosilicate (a molecule that hydrolyses to give one
209 equivalent of orthosilicic acid and four equivalents of ethanol) in diets. Further evidence that
210 silica enhances osteogenesis was provided from preliminary studies with human
211 mesenchymal stem cells (hMSCs) that showed support of porous silica particles in the 100nm
212 – 2 micron size range supported on silk films toward cell attachment and upregulation of
213 osteogenic gene markers (Mieszawska *et al.* 2010).

214 In rats supplemented with silicon in the form described as 'silanol', most likely
215 monomethylsilanetriol, the rate of mineral apposition and bone formation were observed to

increase by 30%, therefore improved trabecular bone volume with a reduction in metaphyseal bone resorption possibly through stimulatory formation of cross-link between collagen and proteoglycans or bone matrix stabilization (Hott *et al.* 1993). Therefore, silicon is thought to be important in the formation of cross-linkages between collagen and proteoglycans in bone formation (Hott *et al.* 1993) where the collagen matrix allows tensile strength sustainability of the bone (Rath *et al.* 2000). *In vitro* studies found that human osteoblasts responded to silica gel to form nodules which eventually mineralized (Anderson *et al.*, 1998). Dietary silicon intake was found to be significantly and positively correlated with cortical bone mineral density in pre-menopausal women (Jugdaohsingh *et al.* 2004). Furthermore, retrospective studies where osteoporotic, post menopausal females were administered intramuscular injections of 50 mg silicon as monomethyl trisilanol twice a week for four months induced significantly higher bone mineral density as compared to pharmacological drug usage (Eisinger and Clairet 1993). In contrast to these findings, a controlled study in overi-ectomised rats fed calcium-replete diets did not increase bone mineral density (Bu *et al.* 2016). More significantly however, the study affirmed an earlier hypothesis that, silicon not only significantly stimulates bone formation but also functions to inhibit bone resorption (Rico *et al.* 2000).

The biochemical influences of silicon regarding bone formation ultimately affect cartilage composition and calcification of active growth sites, typically within the osteoid layer (Arora and Arora 2017). This indicates a direct link to osteoblast proliferation (Shie *et al.* 2011). Additionally, osteoclast formation and bone resorption are inhibited by silicon caused by interactions of intra and inter-cellular signalling pathways (Mladenović *et al.* 2014). This evidence supports the concept that orthosilicic acid, directly effects osteoclastogenesis to promote positive ossification. The precise stage of involvement, at least for RAW264.7 cells

(cells that do not require co-culture with other cell types for osteoclast formation) was identified by increased expression of osteoclast phenotypic genes within the first 24 hours of osteoclastogenesis (Magnusson *et al.* 2021).

Use of Silica in poultry nutrition

The importance of silicon was first established by dietary deprivation studies conducted by (Carlisle 1972) and (Schwarz and Milne 1972). A deleterious effect on growth has been reported to be significant in silicon deprived animals (Schwarz and Milne 1972; Seaborn and Nielsen 1994, 2002; Carlisle, 1986; Brossart *et al.*, 1990), however, without a clear dietary deficiency, no significant effect of Si on growth has been reported (Carlisle 1981b; Elliot and Edwards 1991; Seaborn and Nielsen 1994). In early studies, Si was thought to be inert and pass through the digestive tract with little biological or toxicological impact (Nielsen 1991), and was recommended for addition to poultry diets only under specific experimental conditions (NRC 1994). Bio-available Si has been implicated in a variety of important roles, but the mechanisms of action lack clarity (Perry and Keeling-Tucker 2000).

Research in poultry initially focussed on inclusion of silica in diets as a mineral, but issues with minimal bio-availability made identification of its mode of action and, therefore, production of a viable supplement difficult (Carlisle, 1984; Carlisle, 1986). One very small (n-15 birds) study explored the use of sodium metasilicate as a source of bioavailable silicon and found that, while blood alkaline phosphatase was increased in birds fed diets containing 300g sodium metasilicate per kg diet, several metabolic biomarkers were also significantly raised, suggesting some liver damage may be associated with feeding such a caustic form of silicon at high levels (Tekeli and Zohuri, 1998) and renal damage has been associated with high level silica diets using tetraalkoxyorthosilanes as the silica source (Nakashima, 1994). Another

potential source of silicon, activated crystalline silicon dioxide (Silica+), generated by subjecting micronized silica to electromagnetic radiation, in conjunction with betaine supplementation at 200 ppm and 0.12%, respectively has been reported to improve the growth performance and egg production of quails though it should be noted that the silicon in this product is not bioavailable and allegedly operates through the long lasting effects of its prior treatment to radiation (Ratriyanto et al., 2009). Further studies have been conducted on different poultry and other animals but the mode of action is still not understood

Multiple studies have investigated the addition of silicon to diets in the form of zeolites though these materials have also been used as adsorbents to improve litter quality. Zeolites are highly porous materials composed of hydrated aluminosilicates that can accommodate a wide variety of cations including sodium, potassium and calcium. They possess an infinite, three-dimensional crystalline structure that is able to dehydrate and rehydrate and exchange ions without major structural change, and due to this they have been extensively used as adsorbents within numerous industries (Shariatmadari 2008). The most common zeolites used in the poultry industry to improve litter quality and feed efficiency are Zeolite A, a synthetic zeolite with the chemical composition $\text{Na}_{12}[(\text{AlO}_2)_{12}(\text{SiO}_2)_{12}]\cdot 24\text{H}_2\text{O}$ (Leach et al., 1990; Roland et al., 1993) and a natural zeolite, clinoptilolite, with the chemical composition $\text{CaNa}_4\text{K}_4(\text{AlO}_2)_5(\text{SiO}_2)_{30}\cdot 24\text{H}_2\text{O}$ (Evans, 1989)), though in principle other minerals with a wide range of Al:Si compositions could potentially be used.

Zeolite A has been found to solubilise in the digestive tract and both the Si and the aluminium within the compound are partially absorbed (Roland et al. 1993). Supplementation with Zeolite A has been shown to significantly increase the oral and intramuscular absorption of calcium which was found to decrease the severity and occurrence of tibial dyschondroplasia in broilers (Ballard and Edwards 1988). Further, Zeolite A has been found to increase the bone

ash percentage of broilers with a secondary effect of decreasing litter moisture, thus reducing the severity and occurrence of hock and breast burn (Leach et al., 1990). Of the three mineral elements in zeolites, it has been suggested that Si is the most likely to have caused the beneficial results found (Roland *et al.* 1993), potentially due to the zeolite selectively binding to calcium, which is partially bound to phytate, a storage form of phosphorus in plants. It is, therefore, thought that this improves the actions of the enzyme phytase by allowing it to release the phosphate from the phytic acid/ phytate salt more effectively, increasing phosphorus availability (Edwards 1988). Inclusion of silicon as sodium aluminosilicate in a pH neutral form at a level of 0.75% of the diet was found to improve egg production (Roland 1988). Unfortunately, Zeolites are generally high in aluminium, which is toxic, both to the bird upon ingestion, and, potentially, to the environment upon excretion. Huff *et al.* (1996) found that aluminium toxicity (at levels equivalent to 0.32% of aluminium in diets when introduced as alum) in broilers led to significantly reduced body weight gain, bone ash percentage and reduced serum phosphorus levels, and concluded that aluminium toxicity should be avoided in broilers. Additionally, the addition of 1% natural zeolite, which will add 0.15% aluminium, was found to be toxic to poultry (Shariatmadari 2008).

Variability in results, concerns over adverse effects and problems with diet formulation raise doubts as to the usefulness of zeolites as a feed additive (Shariatmadari 2008). There is also a lack of understanding of the interactions between the various mineral ions contained within zeolites and those already present in the digestive tract of poultry (Watkins and Southern 1992). The high ion exchange is associated with enhanced calcium utilisation as discussed below (Watkins and Southern 1992) . Most recently, in 2021, the EFSA panel on additives and products or substances used in animal feed (FEEDAP) was still not in a position to conclude on the safety and efficacy of the additive sodium aluminosilicate (EFSA 2020).

In addition to zeolites there are many potential sources of bioavailable silicon but these have not, as yet been used to supplement the diet of birds in a commercial setting. These include Horsetail (*Equisetum arvense*) which is often used as a source of Si in human supplements but has been shown to be non-bioavailable when tested *in vitro* (Scholey et al., 2018). Choline stabilised orthosilicic acid and colloidal silica are available as supplements and claim to be bio-available. However, when compared to the levels naturally available in tap water (approximately 13ppm), they contained only 26ppm and <10ppm respectively, making their levels of bio-available Si unlikely to yield a biological response.

A number of Si supplements have been considered for use in poultry production but the concept of differentiating response through bioavailability is relatively new. An older review by Shariatmadari et al. (2008) concluded silicon supplements were of limited efficacy in poultry, but a review of wider species suggested this was due to their low absorbance unless they are presented in a caustic, unpalatable form" (Jugdaohsingh 2007). More recently (Pritchard and Nielsen 2024) systemically reviewed a range of silicon forms used to date for animal studies and concluded that Si consistently positively influences bone and mineral metabolism when around 139 mg Si/kg bird weight/day or more is provided. The authors also noted insufficient detail was reported in many studies, indicating that mechanistic insights into the mode of action for silicon-based effects on bone cannot be made via meta-analysis approaches. Research on male broilers where poultry diets were supplemented with Si in a bioavailable format at silicon doses of 16-80 mg/day are beginning to unveil some of the factors behind the variable efficacy of silicon-based supplements in enhancing skeletal integrity (Scholey et al., 2018; Burton et al., 2020). The key finding of these studies is that the silica must remain in a monomeric form for efficacy. When bioavailability is high through stabilisation of monomeric silica, the supplement level is positively correlated with serum

silicon levels, improved bone mineralization and bone breaking strength (Scholey et al., 2018). Further studies have now begun to more systematically determine biological response in current strains of broilers (Burton *et al.* 2020). Although positive effects of a bioavailable silicon (monomeric silicic acids) containing supplement have been found a clear understanding of the mechanisms by which Si acts and an effective delivery method for supplements have yet to be discovered.

Bioavailability of Silica

Whilst the total Si content of a sample can be quantified with relative ease, the bio-available component/ fraction is more difficult to estimate due to high variability in product behaviour between animal species and indeed variability within different samples of the same ingredient. Alongside dosage and form of Si supplemented, the bio-availability must also be considered as the various forms of Si all vary in their bio-availability. As examples, tetraethylorthosilicate is hydrolysed during digestion to form monosilicic acid (Kayongo-Male and Julson 2008) with a by-product of four equivalents of ethanol. This monomeric form of Si has been shown to be more readily absorbed in the gastrointestinal tract of humans when compared to oligomeric Si, although this has not been confirmed in other species (Jugdaohsingh *et al.* 2000). Other factors which could possibly affect the effect of silicon supplementation are sex (Nielsen 2008) and age (Jugdaohsingh *et al.* 2004) of the animal which also need to be considered, especially when supplementing animals which are rapidly growing, such as broilers.

Nielsen (2008) observed that a novel organic complex arginine silicate inositol (ASI) is as effective as inorganic sodium metasilicate (NaSiO_3) in responding to collagen-induced inflammatory response. Supplementation of arginine silicate inositol complex (comprising of

49.5% arginine, 8.2 % silicon and 25% inositol) to quail during the late laying periods resulted in significant improved bone mineral density. A recent study on male broilers found little effect of silica supplementation (dosed as Siliforce at 13 and 804 mg/day), but it is unclear as to the provenance of the bioavailable silica in this study and it may not be easily absorbed in the bird (Pritchard *et al.* 2020).

The complementary effect of other factors can affect the bioavailability of silicon. For example, supplementation of choline-stabilised orthosilicic acid complementing the effect of calcium/ vitamin D₃ was found to improved bone collagen and femoral bone mineral in humans (Spector *et al.* 2008). This may be of relevance in poultry, particularly for laying hens as a treatment for osteoporosis.

However, it is difficult to accurately measure bioavailable silica. (Elliot and Edwards 1991) commented that analytical values of silicon may possibly be affected by the solubilisation of insoluble silicon material present in the diets making accurate determination difficult. We describe methods to measure monomeric silica above and a recent study by (Prentice 2019) developed a practical protocol to assess soluble, bioactive silicon levels in complex materials such as poultry diets.

Conclusion

Silica can have a positive effect on bone health in poultry but there are several factors which need to be considered to ensure a favourable result. These include, the source of the silica and its bioavailability, the level of supplementation and how it is provided to the birds (i.e. in water or feed). Dietary formulation may also play a role. There is evidence that modern broilers would benefit from additional supplementation of silica in feed, but this needs to be

of a bioavailable form, and supplied in sufficient quantities to support skeletal health with further research being needed to establish a definitive range.

Disclosure statement

No potential conflict of interest was reported by the authors.

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443 nanoparticles [https://www.efsa.europa.eu/sites/default/files/consultation/consultation/Dra](https://www.efsa.europa.eu/sites/default/files/consultation/consultation/Draft-Nano-Technical-Guidance-For-Public-Consultation.pdf)
444 [ft-Nano-Technical-Guidance-For-Public-Consultation.pdf](https://www.efsa.europa.eu/sites/default/files/consultation/consultation/Draft-Nano-Technical-Guidance-For-Public-Consultation.pdf) (accessed 6 August 2020).
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