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Author(s)	Thangavelu, Karthikeyan P.; Kerry, Joseph P.; Tiwari, Brijesh K.; McDonnell, Ciara K.
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Systematic review of novel processing technologies and ingredients for the reduction of phosphate additives in processed meat

K.P. Thangavelu, J.P. Kerry, B. Tiwari, C.K. McDonnell



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1 **Abstract**

2 *Background:* Phosphate additives are used in many processed foods as stabilisers and
3 emulsifiers. They are present in up to 65% of processed meat products. However, consumer
4 preferences for more natural and less processed foods has resulted in the growth of clean
5 label trends, meaning shorter ingredient declarations using fewer ingredients that are
6 unfamiliar to the consumer. Due to the unique characteristics of phosphates, their removal,
7 while maintaining product quality, is challenging.

8 *Scope and Approach:* In this review, phosphate additive-types are discussed, with particular
9 emphasis on their application in processed meat products. Through homeostasis, excess
10 phosphate is readily excreted by individuals with healthy kidney function, but it is
11 acknowledged that there is now a desire to find more acceptable ingredient alternatives. The
12 use of alternative, non-synthetic, ingredients in processed meats such as starch, proteins,
13 seaweeds, hydrocolloids and fibres, as potential phosphate replacers are discussed. Such
14 ingredients may not impart the same quality attributes in meat products as provided by
15 phosphates when used singly, however, adopting hurdle approaches of combining alternative
16 ingredients with novel processing technologies, such as power ultrasound and high pressure
17 processing, may provide the meat industry with alternatives.

18 *Key findings and conclusions:* The key finding of this review is that the interaction between
19 novel technologies and ingredients has not been studied extensively, yet there is evidence for
20 their combined potential. For future studies, non-synthetic ingredients like fibres and starches
21 could be combined with novel processing technologies to improve the interaction between
22 meat proteins and alternative ingredients.

23

Systematic review of novel processing technologies and ingredients for the reduction of phosphate additives in processed meat

Thangavelu, K. P.^{1,2}, Kerry, J. P.², Tiwari, B.¹, McDonnell, C. K.^{1,3*}

1. Food Quality and Sensory Science Department, Teagasc Food Research Centre, Ashtown, Dublin 15, Ireland.

2. School of Food and Nutritional Sciences, University College Cork, Cork, Ireland.

3. CSIRO Agriculture & Food, 39 Kessels Road, Coopers Plains, QLD 4108, Australia

* Corresponding author: ciara.mcdonnell@teagasc.ie

Abstract

Background: Phosphate additives are used in many processed foods as stabilisers and emulsifiers. They are present in up to 65% of processed meat products. However, consumer preferences for more natural and less processed foods has resulted in the growth of clean label trends, meaning shorter ingredient declarations using fewer ingredients that are unfamiliar to the consumer. Due to the unique characteristics of phosphates, their removal, while maintaining product quality, is challenging.

Scope and Approach: In this review, phosphate additive-types are discussed, with particular emphasis on their application in processed meat products. Through homeostasis, excess phosphate is readily excreted by individuals with healthy kidney function, but it is acknowledged that there is now a desire to find more acceptable ingredient alternatives. The use of alternative, non-synthetic, ingredients in processed meats such as starch, proteins, seaweeds, hydrocolloids and fibres, as potential phosphate replacers are discussed. Such ingredients may not impart the same quality attributes in meat products as provided by phosphates when used singly, however, adopting hurdle approaches of combining alternative ingredients with novel processing technologies, such as power ultrasound and high pressure processing, may provide the meat industry with alternatives.

Key findings and conclusions: The key finding of this review is that the interaction between novel technologies and ingredients has not been studied extensively, yet there is evidence for their combined potential. For future studies, non-synthetic ingredients like fibres and starches could be combined with novel processing technologies to improve the interaction between meat proteins and alternative ingredients.

Keywords: Phosphate removal, water holding capacity, power ultrasound, high pressure processing.

37

38 1. Introduction

39 Phosphates are essential for human health as they are required for growth, maintenance and
40 repair of cells and tissues, signalling, energy transfer and other important functions. They are
41 involved in many metabolic pathways and are naturally found in the form of organic esters in
42 foods like egg, meat, potatoes and cereals. In general, the Recommended Dietary Allowance
43 (RDA) of phosphorus (P) for a healthy adult is 700 mg/day (Winger, Uribarri & Lloyd, 2012;
44 Calvo & Uribarri, 2013). Commonly, higher quantities are consumed but excess phosphate is
45 readily excreted by the kidneys. However, individuals with poor kidney function such as
46 those with chronic kidney diseases (CKD) must closely monitor their dietary intake of
47 phosphate to avoid an occurrence of hyperphosphatemia (Calvo & Uribarri, 2013; Kalantar-
48 Zadeh et al., 2010; Ritz, Hahn, Ketteler, Kuhlmann, & Mann, 2012). This is particularly
49 important with the increased use of inorganic P containing additives, such as phosphate
50 (P_2O_5) in processed foods (Winger, Uribarri & Lloyd, 2012).

51 Inorganic phosphates are generally regarded as safe (GRAS) by the United States Food and
52 Drug Administration (FDA) and are used as an effective food additive in many processed
53 food products such as meat, ham, sausages, cheese, canned fish, beverages and baked
54 products. Phosphate addition in US is regulated by FDA regulations that controls the
55 maximum usage levels in food products (Dykes et al., 2019). According to the Scientific
56 Committee of Food by European Communities, the established maximum tolerable daily
57 intake of phosphates is 70 mg/kg body weight expressed as P (Commission, 1991). Since
58 1990, due to increased consumption of processed foods, P intake has doubled from 500
59 mg/day to 1000 mg/day in the American diet (Kalantar-Zadeh et al., 2010). Studies of Leon,
60 Sullivan, & Sehgal (2013) showed that processed food contributed to an extra 700-800 mg of
61 P intake per day and also reported that almost 44% of best-selling groceries in America
62 contained phosphate additives.

63 The increase in the use of phosphates in processed foods may be due to their unique
64 characteristics which often improve product quality. Phosphates serve as buffers,
65 sequestrants, acidulants, bases, gel accelerants, dispersants, precipitants and ion-exchange
66 agents. In the EU, phosphates are classified in the Additive Directive (Regulation EC
67 1333/2008) as belonging to various functional classes such as emulsifier, stabiliser,
68 sequestrants and thickeners and their use is permitted in several processed food categories.
69 Phosphates serve several functions in processed meat such as stabilizing pH, increasing water
70 holding capacity (WHC), decreasing cooking loss, improving texture and sensory qualities
71 and more (Dykes et al., 2019) As per the EU legislation on food additives, the maximum
72 allowed concentration of phosphates in processed meat products is 5000 mg/kg expressed as
73 P_2O_5 content (EC. No. 1333/2008, 2008).

74 There is a growing concern over the sustainable usage of phosphates in food sectors in recent
75 times. The European Food Safety Authority (EFSA) scientists has estimated that the total
76 intake of phosphates from food has exceeded the safety level set by EFSA. With the current

77 average dietary phosphate consumption rate, the scientists have claimed that the dietary
78 exposure to phosphorus level might exceed the acceptable daily intake level in infants,
79 children and adolescents with high phosphate diet (Wyers, 2019). Also, in recent times, there
80 is a general shift towards alternative ingredients in food products with the emergence of
81 consumer trends such as health concerns, sustainability and convenience (Asioli et al., 2017).
82 For sustainable processing, alternatives to synthetic phosphates (e.g. valorisation of
83 functional ingredients from coproducts and waste-streams) could offer an opportunity
84 towards a sustainable circular economy in the food sector. Consumer preference towards
85 natural and less processed food has resulted in the growth of clean label trend. The term clean
86 label first appeared during 1980s which means food products without any E-number additives
87 on the food label where the E numbers stands for codes for the food additives permitted to
88 use within the European Union by the European Food Safety Authority (Asioli et al., 2017).
89 Although, with the growing trend, the term 'clean label' does not possess any clear definition
90 (Asioli et al., 2017). Ingredion (2004) guides clean labelling in Europe as the products that
91 are positioned as natural, organic and/or free from additives/ preservatives which is very
92 similar to the approach of 'natural labelling' by United States Food and Drug Administration
93 (FDA) to refer to the products containing no artificial or synthetic additives in them.

94 In recent years, the clean label trend has become prominent as many new food products
95 contain fewer inorganic additives (Asioli et al., 2017). However, it is important that
96 consumers understand that a functional ingredient, such as P_2O_5 , is only added to the EU
97 Additive Directive by complying with the conditions set out in Regulation 1333/2008. In
98 addition, the Additive Directive sets safe limits on the permitted levels of these ingredients in
99 food products. Nonetheless, there remains an interest in replacing the functional properties of
100 phosphates with clean label alternatives. In that sense, the chosen ingredient must have
101 techno-functionality. The European Food Safety Authority (EFSA) describe ingredients as
102 chemical substances that are added to food as food additives, food enzymes, flavourings,
103 smoke flavourings and sources of vitamins and minerals while additives are any substances
104 that are not normally consumed as a food itself and not normally used as a characteristic
105 ingredients of food, whether or not it has nutritive value, the intentional addition of which to
106 food for a technological purpose in the manufacture, processing, preparation, treatment,
107 packaging, transport or storage of such food results in it or its by-products becoming directly
108 or indirectly a component of such foods (Regulation 1333/2008). Also, with the uncertainty
109 in the clear definition of natural antimicrobials, colourants, sweeteners or antioxidants
110 (Carocho et al., 2015), it is more challenging to define natural techno-functional ingredients
111 when also other aspects like GM-free and allergens are considered. In that sense, there is
112 difficulty in truly classifying 'clean-label' ingredients. Henceforth, all possible alternative
113 ingredients irrespective of clean label status have been discussed in this review in the later
114 sections.

115 Various attempts have been made to replace phosphates in meat with suitable ingredients like
116 starches, proteins, seaweeds, hydrocolloids and fibres (Younis & Ahmad, 2015; Resconi,
117 Keenan, Barahona, et al., 2016a). However, the complete replacement of phosphate in meat
118 with alternative ingredients may have negative effects on appearance, texture and other major

119 product characteristics. For example, use of rice starch as a phosphate replacer in whole
120 muscle cooked hams affected the appearance and sensory qualities of meat (Resconi, Keenan,
121 Barahona, et al., 2016a). Similar results were obtained when the amount of phosphate added
122 to meat was reduced without adding any functional ingredients (Glorieux, Goemaere, Steen,
123 & Fraeye, 2017). Studies have shown that alternative technologies can be effective in
124 enhancing the quality of meat processed with added alternative ingredients. Among the
125 technologies, high pressure processing (HPP) proved to be effective in improving the
126 functionality of meat products by altering the meat structure. The application of HPP in meat
127 products can modify the protein spatial structure resulting in solubilisation of myofibrillar
128 proteins. This can reduce the quantities of salts and phosphates required in processed meat
129 (Tamm, Bolumar, Bajovic, & Toepfl, 2016). For example, reduced-salt cooked ham was
130 produced without any changes in WHC and texture using a salt replacer (KCl) and HPP at
131 100 MPa (Tamm, Bolumar, Bajovic, & Toepfl, 2016). Similarly, ultrasound (US) technology
132 has been widely used to assist effective ingredient distribution and diffusion within food
133 matrices. For example, US has been shown to accelerate the diffusion of salt (McDonnell,
134 Allen, Duane, Morin, Casey, & Lyng, 2017) and salt replacers in pork tissue (Ojha, Keenan,
135 Bright, Kerry, & Tiwari, 2016).

136 In line with the trend for healthier processed meats, comprehensive reviews exist on
137 strategies for sodium reduction (Inguglia, Zhang, Tiwari, Kerry, & Burgess, 2017) and nitrite
138 reduction (Bedale, Sindelar, & Milkowski, 2016) in processed meats. However there is lack
139 of research on phosphate reduction. The objective of this review is to discuss the potential of
140 alternative ingredients and novel processing technologies to reduce phosphates in processed
141 meats.

142 **2. Phosphates in Processed Meat**

143 Phosphates used in processed meat products are the salts of phosphoric acids containing the
144 positively charged metal ions of sodium or potassium. Various legislations, depending on the
145 country, exist on phosphate additive use in foods and further information on this can be found
146 in Dykes et al. (2019). As per European legislations, food grade phosphates are not permitted
147 in fresh meat however they can be added in a limited concentration to meat preparations and
148 meat products (Regulation (EC) 853/2004). According to the Food and Agriculture
149 Organization (FAO) and World Health Organisation (WHO) food standards, the maximum
150 permitted level of phosphates in finished products, whole pieces or cuts and processed
151 comminuted meat products is approximately 5041 mg/kg expressed in P_2O_5 (Codex Standard
152 192, 1995, Balestra & Petracci, 2019)

153 **2.1. Types of Phosphates Used in Meat**

154 Several forms of molecular forms of phosphate (P_2O_5) exist and they are selected depending
155 on their required function in the food matrix. Phosphates are classified according to the
156 number of phosphorus atoms sharing oxygen atoms (Lampila & Godber, 2002). They are as
157 ortho- or monophosphates with one phosphate molecule, di- or pyrophosphates with two
158 phosphate molecules, triphosphates with three phosphate molecules and polyphosphates with

159 more than three phosphates molecules. The molecular structures of phosphates are ring or
160 metaphosphates, chain /linear phosphates or ultra /branched phosphate structures with a
161 combination of ring and linear phosphates.

162 Only linear phosphates are permitted to be used in processed meats. The commonly used,
163 Graham's salt (sodium hexametaphosphate) is a linear phosphate with P_2O_5 content of about
164 60-70% (Feiner, 2006; Lampila & Godber, 2002). Sodium tripolyphosphate (STPP) is
165 commonly mixed with sodium hexametaphosphate (SHMP), tetrasodium pyrophosphate
166 (TSPP) or sodium acid pyrophosphate (SAPP) for use in meat products like ham, bacon,
167 frankfurters, bologna, precooked breakfast sausages, delicatessen meats, breaded chicken
168 products and injected poultry pieces (Lampila, 2013). Different types of phosphates are used
169 for different meat products based on the product process and formulation as explained by
170 Long et al. (2011). For example, long- chain polyphosphates with better solubility are used to
171 prepare brine solutions for ham whereas short-chained phosphates are used for emulsified
172 products like sausages where the added phosphates act on the protein instantly (Feiner, 2006).

173 **2.2. Functionality of phosphates in meat**

174 Phosphates have various functions such as buffering, water-binding, emulsification, colour
175 stability, oxidation inhibition, antibacterial activity and protein dispersion properties but are
176 most commonly used in meat products for their emulsifying and stabilising capabilities,
177 which largely affect the water holding capacity (Nguyen, Gal, & Bunka, 2011).

178 Water holding capacity is the ability of meat products to retain its inherent water when an
179 external pressure or force is exerted upon it, as well as during its storage period thereby
180 affecting weight and juiciness (Gyawali & Ibrahim, 2016;). In general practice, salting is one
181 of the oldest techniques for preserving meat and aimed to increase water holding capacity
182 which is obtained only when low quantity is added (Feiner, 2006). Phosphates additives may
183 interact against water losses due to several underlying mechanisms importantly, phosphates
184 affect the intrinsic pH of meat by moving from the isoelectric point (pI). For this reason, most
185 phosphates used in meat products as alkaline (Long et al., 2011), with the exception of
186 sodium acid pyrophosphate which is acidic in nature and are used for various functions
187 (Lampila, 2013). This increase in pH results in the increased electrostatic repulsion between
188 the proteins allowing for water entrapment (Puolanne, Ruusunen, & Vainionpaa, 2001). This,
189 in turn, results in swelling of the muscle fibres and activation of proteins. This swollen and
190 active protein traps and immobilises water added to the meat. Hence, the WHC is increased
191 and this is especially true in case of polyphosphates like SHMP and STPP (Glorieux et al.,
192 2017).

193 Phosphates also increase the WHC of meats by sequestering the metal ions such as Ca^{2+} ,
194 Mg^{2+} , Fe^{2+} and Fe^{3+} present in the actomyosin complex (Long et al., 2011). When added,
195 phosphates can bind with ions present in the actomyosin complex which is formed during
196 rigor mortis. Dissociation of actomyosin into actin and myosin increases the solubilisation of
197 meat proteins through depolymerisation of thick and thin filaments which leads to increased

198 WHC, emulsifying and gelling properties (Glorieux et al., 2017; Puolanne & Halonen, 2010).
199 This can also have a positive impact on the textural characteristics of meat products.

200 Phosphates also work synergistically with NaCl for improved product quality. This is mainly
201 due to the positive effect of NaCl on the solubility of myofibrillar proteins. The Cl⁻ ions
202 induces electrostatic repulsion between the meat proteins and results in swelling of the meat.
203 Generally, a minimum concentration of 0.6M of NaCl is required to extract myofibrillar
204 proteins from the muscle but this amount of NaCl can be effectively reduced by adding
205 phosphates (5000 mg/kg) to meat product formulations. Thus, by phosphate facilitating
206 actomyosin dissociation, myosin becomes more easily solubilised by NaCl which in turn
207 immobilises large amounts of added water. Studies of Schwartz & Mandigo (1976) proved
208 the synergic effect of salt (0.75%) and STPP (0.125%) on restructured pork in improving the
209 WHC, eating texture, aroma, flavour, cooking loss and juiciness upon storage at -23 °C for
210 four weeks when compared to salt alone. Later, Knight & Parsons (1988) were one of the first
211 to provide a detailed description on the structural changes to the myofibril following NaCl
212 and polyphosphate treatments. Numerous studies were carried out which demonstrate this
213 synergy and the WHC properties of added phosphates on meat products (Puolanne et al.,
214 2001; Sen, Naveena, Muthukumar, Babji, & Murthy, 2005).

215 Phosphates and NaCl also helps the emulsion stability of meat products by allowing myosin
216 to form a tacky protein substance upon mixing, known as the exudate which forms a gel upon
217 heating (Lampila, 2013). This helps in binding the pieces of meat in production of reformed
218 products. This development of water- fat- protein emulsion matrix is also critical in
219 frankfurter and bologna production. The application of phosphates and NaCl in meat
220 formulations results in myosin solubilisation thereby orienting its hydrophobic tail around fat
221 droplet and binding its hydrophilic end with water (Lampila & McMillin, 2017). When
222 heated, the myofibrillar proteins undergo several structural changes which can strengthen the
223 gel structure and emulsion stability, thereby increasing WHC and reducing cooking loss.
224 However, the temperature ranges for the structural transitions are dependent on several
225 factors within the protein system (e.g., species, pH, ionic strength, ingredients) (Chen et al.,
226 2017). To prove the emulsifying property, Anjaneyulu, Sharma, & Kondaiiah (1990) studied
227 the effect of blends of phosphates (65% TSPP, 17.5% STPP and 17.5% SAPP) on buffalo
228 meat patties with added 2% NaCl. The results showed improved emulsifying capacity and
229 emulsion stability with increased WHC.

230 The chelating properties of phosphates also provide some anti-oxidative ability. Lipid
231 oxidation may be inhibited by phosphates chelating with metal ions that otherwise could
232 catalyse oxidation of proteins like haemoglobin and lipid like phosphor-lipids. Therefore,
233 their inclusion in products could play a role in preventing colour degradation and generation
234 of rancid off-flavours (Feiner, 2006; Long et al., 2011; Dykes et al., 2019). Studies of
235 Fernandez-Lopez, Sayas-Barbera, Perez-Alvarez, & Aranda-Catala (2004) showed that
236 addition of sodium tripolyphosphate (0, 0.15 or 0.30%) on pork meat reduced lightness and
237 stabilised the percentage of oxymyoglobin. However, no effect was seen on redness,
238 yellowness, chroma and hue saturation of meat colour. Studies by Baublits, Pohlman, Brown,
239 & Johnson (2005, 2006); Fernandez-Lopez, Sayas-Barbera, Perez-Alvarez, & Aranda-Catala,

240 (2004) help in understanding the functions of phosphate mixtures on colour properties of
241 meat products.

242 Phosphates can also act as preservative with slight bacteriostatic effect against some gram-
243 positive bacteria. However, it is less significant in meat products as greater concentration of
244 phosphates or additional preservatives will be required for effective antibacterial activity
245 (Feiner, 2006; Long et al., 2011).

246 **3. Strategies to reduce phosphates in meat products**

247 Consumer's awareness of food additives and their interests towards clean label food products
248 has led to a need to reduce and/or remove phosphates and often, replace them with various
249 functional ingredients that can serve as fillers, binders, emulsifiers and stabilisers. This can be
250 achieved by product reformulation and/or process modification. Figure 2 summarises
251 strategies for replacing phosphates in meat with suitable phosphate replacers and novel
252 processing technologies. Various novel technologies are discussed in brief, while emphasis is
253 placed on the discussion of US and HPP which show more potential in the application of
254 phosphate-free meat products. Thus, this review will discuss the possible ingredient and
255 technology approaches for phosphate reduction in meat products with respect to specific
256 quality characteristics including water-binding, emulsion stability, sensory, texture, colour
257 and oxidative status.

258 **3.1 Ingredient strategies for phosphate reduction in processed meat**

259 There are various alternative functional ingredients for phosphates available such as native
260 and modified starches, proteins, fibres, hydrocolloids, seaweeds, vegetable powders,
261 carbonate salts and high pH alkaline solutions. These ingredients have potential to off-set
262 some quality losses when phosphates are removed or reduced (Resconi, Keenan, Barahona, et
263 al., 2016b; Glorieux, Goemaere, Steen, & Fraeye, 2017). Alternative ingredients can be
264 added in small quantities to replicate some of the functionalities of phosphates in meat
265 products. As discussed earlier, the ingredients irrespective of their clean label status are
266 discussed in this section for their ability to replace the various techno-functionality of
267 phosphates such as WHC and cook yield, emulsion stability, textural and sensorial properties.
268 Table 2 lists the various ingredients that can be used as phosphate replacers based on their
269 ability to produce specific techno-functionality in meat products.

270 **3.1.1. Water-binding and emulsifying properties**

271 One of the main techno-functionalities of phosphates in meat products is increasing the water
272 holding capacity (WHC) and cooking yield (Nguyen, Gal, & Bunka, 2011). Ingredients like
273 starches, proteins, fibres, hydrocolloids and bicarbonate salts can also improve WHC and
274 cook yield when used in meat products (Petracchi et al., 2013). Many studies have been made
275 on these ingredients to improve the WHC of meat products without any added phosphates
276 (Resconi, Keenan, Garcia, et al. 2016b; Prabhu & Husak, 2014; Casco et al., 2013; Sousa et
277 al., 2017). For example, the study of Wachirasiri et al. (2016) investigated the phosphate
278 replacing ability of sodium bicarbonate at low concentration for freezing of white shrimp

279 (*Penaeus vannamei*). The shrimps were treated with sodium bicarbonate (NaHCO_3), lysine
280 and sodium bicarbonate – lysine mixture at various concentrations and frozen. Results of
281 thawing yield, cooking yield, colour, textural values were compared with those of sodium tri
282 polyphosphates (STPP) treated shrimps. It was concluded that the shrimps treated with
283 NaHCO_3 /lysine each at 1% (w/v) improved the water holding capacity and cooking yield
284 (100.45%, w/w) similar to that of STPP treated samples (101.73%, w/w), proving that
285 NaHCO_3 can act as a possible phosphate replacer. In a study by Casco et al. (2013),
286 SavorPhos - mixture of citrus flour that is rich in fibre content, all-natural flavourings and
287 less than 2% sodium carbonate is used as phosphate replacer in water and oil-based
288 marinades in rotisserie birds and boneless-skinless breast. SavorPhos when used in water
289 marinade resulted in equal performance in WHC and cook loss as that of control phosphate
290 blend whereas when used in oil marinade, it increased WHC and decreased cook loss. The
291 study of Bertram, Meyer, Wu, Zhou, & Andersen (2008) elucidated to the structural changes
292 induced by sodium bicarbonate (NaHCO_3), salt (NaCl) and tetrasodium pyrophosphate
293 ($\text{Na}_4\text{O}_7\text{P}_2$) in enhanced pork by use of low-field nuclear magnetic resonance and confocal
294 laser scanning microscopy. It was found that sodium bicarbonate (NaHCO_3) resulted in
295 increased solubilisation of proteins and a higher degree of swelling of the myofibril, resulting
296 in increased yield and reduced cooking loss (Bertram et al., 2008).

297 Similarly, starches have potential to affect the water-binding properties of meat. In the study
298 made by Gencelep et al. (2015), both physically and chemically modified starches are used
299 to study the steady state and dynamic rheology of meat emulsions. In the study, acid modified
300 starch (AMS), dextrinized modified starch (DMS) and pre gelatinised modified starch (PGS)
301 is compared with native potato starch (NPS). From the results, it was concluded that the meat
302 emulsions with PGS is a good thickener and can be used as a stabilizer for meat emulsions
303 due to their higher water and oil binding capacity, particle size, intrinsic viscosity and
304 solubility than NPS. Thus, there is evidence that starches can be modified to impart specific
305 characteristics in meat products. It should be noted that physically modified starches are
306 modified without enzymatic hydrolysis and chemicals and therefore, are classified as native
307 starches, while often having more functionality than native starches.

308 Similar to WHC, studies have been made to prove the emulsion stabilizing property of
309 different ingredients in meat emulsions. Native starches, fibres, seaweeds, vegetable powders
310 and hydrocolloids can be used to improve emulsion stability in meat batters (Petracci et al.,
311 2013). Studies of Youssef & Barbut (2011) revealed that the addition of soy protein isolates
312 to lean meat emulsion batters increased moisture retention; increased emulsion stability and
313 decreased cook loss. Similarly, Paglarini et al. (2018) studied the influence of carrageenan on
314 WHC of meat emulsion gels at different concentrations mixture using Plackett –Burman
315 design. Results of WHC tests revealed that carrageenan addition increased the WHC of
316 emulsion mixture and improved emulsion stability. In another study made by Younis &
317 Ahmad (2015), apple pomace powder obtained from apple processing used as a functional
318 ingredient in buffalo sausages effectively improved the emulsion stability, water activity and
319 cooking yield.

320 While research has shown that many ingredients can increase the water-binding and
321 emulsification of meat matrices, as shown in Table 2, protein solubilisation and muscle
322 binding remain a challenge when phosphates are removed. That is because these ingredients
323 do not act on the acto-myosin complex like phosphate (Prabhu & Husak, 2014). One specific
324 challenge is in binding of pieces to create reformed products as for it is difficult to form a
325 sticky exudate without phosphate, for which transglutaminase could be an option (Feiner,
326 2006; Lampila, 2013).

327 3.1.2. Texture and sensory characteristics of phosphate-free meat products

328 Phosphates plays a major role in the textural properties of meat products. Many studies have
329 assessed the effect of different ingredients on the textural and sensory characteristics of meat.
330 In a study made by the Cox & Abu-Ghannam (2013), adding seaweed, *H. elongata*, at
331 different concentrations (0, 10, 20, 30 & 40%) to beef patties resulted in improved water
332 binding properties, decreased the cooking losses, increased tenderness and sensory properties.
333 Similar results were obtained when the *H. elongata* (5.5%) was incorporated in frankfurters
334 and breakfast sausages whereby the hardness and chewiness of the products were also
335 enhanced upon their addition (Lopez-Lopez, Cofrades, Ruiz-Capillas, & Jimenez-Colmenero,
336 2009). A recent study by Choe et al. (2018) using winter mushroom powder
337 (*Flammulina velutipes*) as a phosphate replacer in emulsion-type sausages showed that adding
338 1% of mushroom powder inhibited lipid oxidation and produced better textural characteristics
339 in sausages.

340 Though the ingredients have various advantages of replacing phosphates, there are some
341 negative attributes imparted in the meat products. For example, although there was improved
342 water holding capacity and decreased cooking and purge losses, studies revealed that
343 incorporating pea proteins in meat products produced negative impact on the textural attribute
344 (Pietrasik & Janz, 2010; Sun & Arntfield, 2012). Studies of Resconi, Keenan, Garcia, et al.
345 (2016b) suggested that a reduction in phosphate content can be made by adding significant
346 amount of starch to the reformed hams without compromising the quality. However, a
347 reduction in the sensory quality was observed when phosphates are completely replaced by
348 rice or potato starch. Hence, some ingredients have demonstrated potential and could be
349 optimised with further research but it remains challenging to replace phosphates due to their
350 multifunctionality in meat products.

351 3.1.3. Colour and oxidative stability

352 In principle, phosphates play a small role in controlling the lipid oxidation and improving the
353 colour stability of the meat products (Choe et al., 2018). While the majority of research has
354 been conducted with emphasis on other quality parameters, some research has been
355 conducted on the effect of phosphate alternatives on colour and oxidative stability. In a study
356 of Choe et al. (2018) it was shown that there is no significant colour difference in the
357 emulsion type sausages when added with winter mushroom powder. In contrast, in the study
358 made by Choi et al. (2016), addition of apple pomace fibre to fat-reduced chicken sausages
359 affected the colour of the product. Thus, the colour of the meat products may vary according

360 to the type of ingredients used as some ingredients may have naturally darker colour than the
361 meat or phosphates and thereby contribute to the colour, independent of oxidative status.

362 In general, studies of high pH alkaline solutions such as sodium chloride, ammonium
363 hydroxide, sodium hydroxide solutions show potential to replace phosphates in the meat
364 enhancement solutions (Parsons et al., 2011a; Parsons et al., 2011b; Rigdon et al., 2017).
365 Using the high pH alkaline solutions as enhancement solution increase the pH of the meat
366 system resulted in increased water holding capacity, improved tenderness and colour. For
367 example, study of Parsons et al., (2011a) using a brine containing 1% ammonium hydroxide
368 (AHT) in beef strip loins demonstrating that phosphates can be replaced with improved
369 colour and retail display properties. However, due to the increased pH, the microbial load of
370 the AHT strip loins were higher when compared to the control. Hence, care must be taken to
371 optimise the pH without affecting the shelf life of the product

372 In relation to oxidative stability, studies of Bao, Ushio, & Ohshima, (2008) demonstrated an
373 increase in pH and a decrease in oxidation when 5ml of mushroom extract containing
374 ergothioneine was added to beef and fish meats thus improving the retail display
375 characteristics. Also, the study of Choe et al. (2018) showed there is no significant difference
376 between the oxidation of sausages treated with phosphates or winter mushroom powders.
377 Thus, ingredients which do not modify colour and antioxidative activity could contribute
378 towards phosphate reduction in meat.

379 **3.2 Processing technologies for phosphate reduction in processed meat**

380 The consumer demand for high quality and less processed foods with minimal ingredients
381 and additives has resulted in the shift towards innovative non-thermal clean processing
382 technologies like power ultrasound, high pressure, plasma technology, pulsed X- ray,
383 ultrafiltration and electrical methods. These non-thermal technologies can overcome the
384 disadvantages of thermal technologies by maintaining the sensory and nutrient value and
385 ensuring microbial safety of the processed foods (Inguglia et al., 2017). The mechanisms of
386 some technologies could assist in phosphate reduction in meat products when used alone or in
387 combination with phosphate alternatives. Cold atmospheric plasma, pulsed UV light and
388 ozone are used as surface treatment and mainly used for surface decontamination of
389 pathogens in meat products (Troy et al., 2016). Pulsed electric fields (PEF) and Shockwave
390 (SW) are two emerging technologies for meat application. Both technologies have the
391 potential to rupture the meat matrix and thereby could improve ingredient interaction with the
392 proteins. A study by Toepfl, Heinz and Knorr, (2006) demonstrated that PEF could improve
393 the WHC, yield and texture of injected hams containing phosphate. Similarly, while SW has
394 not been assessed directly for phosphate removal, in a study on sausages containing various
395 levels of salt (1.8-1.9 % or 2.2-2.4 % NaCl), SW treatment reduced the cook loss by 2% in
396 the 1.8-1.9% NaCl sausages (Heinz, 2014). Recent comprehensive reviews of the
397 mechanisms and potential of PEF and SW for the tenderisation of meat exist (Troy et al.,
398 2016; Warner et al., 2017). However, their application on the processed meat is limited.
399 Hence, ultrasound (US) and high pressure processing (HPP) will be discussed in more detail.
400 Specific focus is put on their interaction with alternative ingredients in creating minimally

401 processed meats with reduced or removed phosphate, which is a novel approach to cleaner
402 labelled processed meats.

403 **3.2.1 Power Ultrasound**

404 Power ultrasound is a non-thermal processing technology that uses sound energy of
405 frequencies higher than human audible range (>20 kHz) and lower than microwave
406 frequencies (10 MHz). The detailed information on various physical and chemical
407 mechanisms that causes ultrasonic effects can be found in several comprehensive reviews
408 (Alarcon-Rojo, et al., 2015; Alarcon-Rojo, et al., 2019). Studies have been conducted using
409 ultrasound for microbial inactivation in meat (Kang et al., 2017a), meat tenderness (Warner et
410 al., 2017; Chang et al., 2015), accelerated meat processing like brining and curing
411 (McDonnell, Lyng, Arimi, & Allen, 2014; Ojha et al., 2016). In terms of the possibility of
412 US in a phosphate reduction strategy, this could include improved functionality of ingredients
413 for meat application by pre-treatment with US, improved ingredient distribution within the
414 meat matrix or the effect of US on meat quality parameters when applied to the manufactured
415 product.

416 3.2.1.1. Water-binding and ingredient distribution properties

417 US can also be used to modify the WHC and oil holding capacity (OHC) of added alternative
418 ingredients without any adverse effect on their properties. Studies of Resendiz-Vazquez et al.
419 (2017) showed that there is a significant change in the WHC and OHC of jackfruit seed
420 protein isolates when treated with high intensity ultrasound for 15 min at 20 kHz with power
421 input level of 200, 400 or 600 W. Further, Kohn et al. (2016) studied the effects of US on the
422 water absorption capacity of added ingredients. When two groups of ingredients (proteins and
423 polysaccharides) were treated in an ultrasonic water bath at 40 kHz frequency for 15 and 30
424 min, significant increases in the water absorption capacity (WAC) for polysaccharides were
425 observed. In a recent study, Pinton et al. (2019) found that 18 min of US (25 kHz, 230W)
426 could account for a 50% reduction in phosphate levels in meat emulsions.

427 US has been shown to accelerate mass transfer into the meat matrix. Studies of Ozuna, Puig,
428 Garcia-Perez, Mulet, & Carcel (2013) assessed the application of ultrasound on pork brining
429 kinetics and found that US increased the NaCl and the moisture effective diffusivities.
430 Similarly, research by McDonnell, Lyng, Arimi, & Allen (2014) proved that meat curing time
431 can be reduced by up to 50% by operating US at pilot-scale on pork curing. In the same
432 study, there was no significant effect on the quality and sensory properties of sonicated meat.
433 Ojha et al. (2016) also showed that ultrasound treatment during pork brining could accelerate
434 the diffusion of a commercially available salt replacer which targets sodium replacement.
435 Thus, US can accelerate the diffusion of salt and possibly, other additives in meat during
436 brining.

437 Therefore, this combined ability of US to reduce additive requirements, improve ingredients
438 distribution in meat products and increase the functionality of ingredients could be applied as
439 hurdle approach towards phosphate reduction in meat products and warrants further
440 investigation.

441 3.2.1.2. Texture/sensory properties

442 Application of ultrasound through a biological structure produces compressions and
443 depressions in the microstructure resulting in cavitation and studies have indicated that this
444 results in microstructural changes to the meat matrix (Siro et al., 2009). A number of
445 experiments have studied the effect of ultrasound on the textural properties of meat (Alarcon-
446 Rojo et al., 2015). As discussed in a comprehensive review by Warner et al. (2017) the effect
447 of US on meat texture is dependent on many processing parameters, thus, the results in the
448 literature are variable. Similarly, Pinton et al. (2019) found that the efficiency of ultrasound
449 in meat processing was dependent on processing parameters when applying US (25 kHz,
450 230W) for 9 or 18 min to meat emulsions. It was found that 18 min of US could off-set
451 defects caused by up to 50% phosphate reduction including increased cohesiveness and
452 higher texture scores in sensory analysis. On the other hand, other authors have found no
453 change to textural properties of meat sonicated during brining, however they did find
454 accelerated diffusion of NaCl (McDonnell et al., 2014). Therefore, there is evidence that US
455 has the ability to reduce additive requirements, improve ingredients distribution and off-set
456 quality defects caused by phosphate reduction. However, the optimisation of several process
457 parameters is required when applying US to meat.

458

459 3.2.1.3. Oxidative stability

460 Ultrasound treatment can lead to the formation of free radicals that might accelerate lipid
461 oxidation in meat products. Studies showed that using high intensity ultrasound on meat
462 products increases the lipid and protein oxidation that could affect the textural properties
463 (Chang et al., 2015; Kang et al., 2017b; Alarcon-Rojo, et al., 2019). However, they can be
464 controlled using various factors like pressure, temperature and ultrasound settings (Pinton et
465 al., 2019). In the study made by Pinton et al. (2019), there is no increased lipid oxidation
466 when cooked meat emulsions were treated with ultrasonic power of 25kHz for 9 and 18
467 mins. Thus, optimisation of processing parameters is important to maintain quality
468 parameters.

469 4.2. High Pressure Processing

470 High Pressure Processing (HPP) is another important non-thermal processing technology.
471 HPP subject food products to very high hydrostatic pressure from 300-600 MPa and mild
472 temperatures (<45°C) which can inactivate micro-organisms and enzymes in food products
473 without any effect on product colour, flavour and nutritional composition (O'Flynn et al.,
474 2014). More detailed information on effects of HPP mechanism on meat products are found
475 in several studies (Hygreeva & Pandey, 2016; Chen et al., 2017).

476 3.2.2.1. Water-binding properties

477 HPP can cause conformational changes in proteins leading to protein denaturation,
478 aggregation or gelation which helps to improve the functionality of comminuted meat
479 products. In doing so, HPP also plays a major role in improving the water holding capacity of

480 meat products. Various studies have reported on the effect of HPP on the water binding
481 capacity (WBC) of meat products (Zheng, Han, Yang, Xu, & Zhou, 2018). Pressurisation of
482 meat products resulted in an improvement in gel-forming properties of meat proteins thus
483 enhancing the WHC and textural characteristics of meat product. Results from various studies
484 showed that HPP increased the emulsion stability, chewiness, cohesiveness, hardness,
485 gumminess and decreased cooking and purge loss in meat products (Inguglia et al., 2017).
486 Studies of Crehan, Troy, & Buckley (2000) assessed the effect of HPP on frankfurters with
487 various salt levels and reported notable improvements in the juiciness and textural properties.
488 Studies have also shown that HPP plays a major role in replacing additives in meat products
489 by promoting the cohesive properties of meat particles. Heat set gels formed after HPP
490 treatment in comminuted meat products have improved characteristics with both low and
491 high salt concentrations (Ikeuchi, Tanji, Kim, & Suzuki, 1992). Grossi et al. (2012) studied
492 the effect of HPP treatment on salt-reduced sausages with carrot fibre and/or potato starch as
493 salt replacers. Pork sausages with different formulations of salt, carrot fibre and/or potato
494 starch were treated with 400, 600, or 800 MPa for 5 minutes at 5 or 40 °C. Results of WBC
495 tests proved that the incorporation of HPP and a new functional ingredient improved the
496 water holding capacity of low salt sausages to the same level as high salt sausages. From the
497 experiment it was concluded that HPP at 600 MPa can reduce the salt content of hydrocolloid
498 containing pork sausages from 1.8 to 1.2% without any negative impact on the WBC, texture
499 and colour. Similar results were obtained when salt reduced hams were treated with 100 MPa
500 (Tamm et al., 2016).

501 3.2.2.1. Texture and sensory properties

502 O'Flynn et al. (2014) investigated the use of high pressure processing on phosphate-reduced
503 breakfast sausages and its effect on physicochemical and sensory characteristics. Sausages
504 with 0, 0.25, 0.5% phosphate content were manufactured using the raw minced pork meat
505 which was pre-treated with HPP at 150 or 300 MPa for 5 minutes. Analysis found that HPP
506 treated phosphate-free sausages had improved emulsion stability compared to the non-HPP
507 treated control. However, a slight decrease in the juiciness was observed for the sausages
508 treated with HPP. From the comprehensive results it was concluded that the administration of
509 HPP treatment at 150 MPa for 5 minutes had a positive effect in reducing the phosphate
510 content in low fat breakfast sausages to 0.25% without any negative impact on the functional
511 characteristics. Despite various successful results, evidences from experiments showed that
512 there were some negative effects on the sensory and acceptability characteristics on the meat
513 products. Decreased functional properties in sausages were observed when they are treated
514 with HPP at 300 MPa (O'Flynn et al., 2014). Application of high pressure over 400 MPa
515 reduced the WHC in meat batters thus affecting the sensory characteristics of the meat
516 product.

517 3.2.2.3. Colour and oxidative stability

518 The study of Fuentes et al., (2010) showed that application of high hydrostatic pressure of
519 600 MPa for 6 minutes increased the lipid and protein oxidation in vacuum packaged Iberian
520 dry cured ham. Similar increase in the protein and lipid oxidation were obtained when high

521 pressure of 600 MPa was applied to the cooked and raw ground beef for 5 minutes (Jung et
522 al., 2013). Other disadvantages of HPP are a reduction in sensory properties due to the
523 resistance offered by food enzymes and pressure resistant bacterial spores resulting in
524 spoilage of food (Inguglia et al., 2017). This highlights the importance of optimisation
525 processes which is suitable for processing parameters.

526 Nonetheless, the ability of HPP to solubilise and extract myofibrillar proteins, improve WHC
527 and ingredient interaction in meat helps in the reduction of additives like phosphates. Indeed,
528 there are a lack of studies assessing the interaction of HPP and alternative ingredients as
529 phosphate replacers in meat products.

530 **5. Conclusion (Future Trends)**

531 With focus on consumer's preference towards clean label healthier food products, this review
532 discussed the potential options available to create processed meat with reduced or removed
533 phosphate additives. Different potential phosphate replacers and advanced processing
534 technologies were outlined to overcome the phosphates added in meat products. Although
535 studies proved that there were many advantages with these alternative techniques, there are
536 often negative effects on the quality of the meat products. Studies on phosphate reducing
537 strategies should be made considering the physicochemical and sensory characteristics of
538 processed meat products. Combining novel technologies like HPP and US with potential
539 phosphate replacers could be one possible solution. However, cost -analysis study of these
540 technology usage would be required in order to ensure their commercial viability in the
541 future.

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549

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Table 1. List of phosphates used in meat products with corresponding P₂O₅ content adapted from Nguyen et al. (2011) and Lampila & McMillin (2017)

Common names	Chemical structure	pH (1% solution)	P ₂ O ₅ content (%)	E* number
Monosodium phosphate		4.4-4.8	59.2	E339(i)
Disodium phosphate		8.6-9.4	50.0	E339(ii)
Trisodium phosphate		11.9-12.5	43.3	E339(iii)
Tetrasodium pyrophosphate		9.9-10.7	53.4	E450(iii)
Sodium acid pyrophosphate		4.0-4.4	64	E450(i)
Sodium tripolyphosphate or pentasodium phosphate		9.5-10.2	57.9	E451(i)
Sodium hexametaphosphate		6.3- 7.3	69.6	E452(i)
Potassium monophosphate		4.4-4.8	52.1	E340(i)
Dipotassium phosphate		8.6-9.4	40.8	E340(ii)
Tripotassium phosphate		11.9-12.5	33.4	E340(iii)
Tetrapotassium pyrophosphate		10.0-10.5	43.0	E450(v)
Potassium tripolyphosphate		9.5-10.2	47.5	E451(ii)

*E numbers – stands for the codes for the food additives permitted to use within the European Union by the European Food Safety Authority. Roman numerical in the E numbers denotes the different type of phosphate with same cationic group. For example, E339 (i), (ii), (iii) denotes the different types of sodium phosphate groups while E450 (i), (iii) denotes the different sodium pyrophosphates.

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Table 2 List of different ingredients that can be used as a potential phosphate replacer based on the techno-functionality they impart in different meat products.

Techno - functionality	Ingredients	Meat product	Effects	Reference
Water holding capacity & cook yield	Potato starch and sodium carbonate	Pork loin	Improved cook yield	Prabhu & Husak (2014)
	Rice starch and fructo-oligosaccharides	Cooked hams	Improved WHC and negative cook yield	Resconi, Keenan, Barahona, et al. (2016a)
	SavorPhos containing citrus fibre	Marinades for rotisserie birds and boneless-skinless breast	Same WHC and cook yield when compared to the control	Casco et al. (2013)
	Pea and carrot fibre	Comminuted meat products	Increased WHC	Petracci et al. (2013)
	Seaweed <i>H. elongata</i>	Beef patties	Improved water binding and cooking yield	Cox & Abu-Ghannam (2013)
	Dehydrated beef protein	Brines for beef steaks	Decreased total fluid loss	Lowder et al. (2011)
	Cuttlefish gelatine	Turkey meat sausages	2.5% increase in WHC	Jridi et al. (2015)
	Pea protein	Comminuted meat products	Improved WHC and decreased cook and purge loss	Pietrasik & Janz, 2010; Sanjeewa, Wanasundara, Pietrasik, & Shand (2010)
	Rye bran, oat bran and barley fibre	Low-fat sausages and meatballs	Oat bran (6%) increased gelling properties, decreased frying loss in sausages while rye bran (2.1%) improved sensory characteristics	Petersson, Godard, Eliasson, & Tornberg (2014)
Carrageenan	Tumbled meat products	Improved cook yield, WHC	Petracci et al. (2013)	

	Sugarcane dietary fibre	Low-fat meat batter	Increased water and fat-binding. 2% sugarcane dietary fibre resulted in comparable acceptability to the control	Zhuang, Han, Kang, Wang, Bai, Xu, & Zhou (2016)
	Carrageenan	Turkey sausages	Increased WHC	Ayadi et al. (2009)
	Sodium bicarbonate	Cooked chicken breast fillets	Increased WHC and texture properties	Mudalal et al. (2014)
	Microbial transglutaminase	Pork batter gel	Decreased cooking loss with increase in transglutaminase concentration	Pietrasik & Li-chan (2002)
	Sodium bicarbonate	Marination of broiler breast meat	Higher water retention and improved cook yield	Petracci et al. (2012)
	Sodium bicarbonate	White shrimp	Improved WHC and cook yield	Wachirasiri et al. (2016)
Emulsion stability	Apple pomace powder	Buffalo sausages	Improved emulsion stability and water activity	Younis & Ahmad (2015)
	Apple pomace powders	Reduced fat chicken sausages	Increased emulsion stability	Choi et al. (2016)
	Carrageenan	Meat emulsion gels	Increased emulsion stability	Paglarini et al. (2018)
	Makgeolli lees fibre	Reduced fat pork frankfurters	A 10% fat reduction can be achieved, with similar product characteristics, by 2% fibre addition	Choi, Park, Kim, Hwang, Song, Choi, Kim (2013)
	Pig plasma transglutaminase	Low-salt chicken meat balls	Increased gel strength and increased emulsion stability	Tseng, Liu, chen (2000)
	Mushroom powder <i>Agaricusbisporus</i>	Meat emulsion batters	Increase in emulsion stability	Kurt & Gencelep (2018)

Textural and Sensory Quality	Winter mushroom powder	Emulsion type sausages	Inhibited lipid oxidation and better textural properties	Choe et al. (2018)
	Rice starch and potato starch	Reformed ham	Reduction in sensory qualities were observed when phosphate is completely removed	Resconi, Keenan, Garcia, et al. (2016b)
	Soy hull pectin and insoluble fibre	Beef burger patty	Pectin minimized water loss and texture defects	Kim, Miller, Lee, & Kim (2016)
	Wheat fibre	Reduced meat and fat burger patty	Up to 3.75 g fibre addition achievable with the same sensory acceptance as the control	Carvalho, Pires, Baldin, Munekata, de Carvalho, Rodrigues, Trindade (2019)
	Citrus fibre	Uncured all-pork bologna and oven-roasted turkey breast	Products had similar physical, chemical and sensory characteristics to products with phosphates in them	Powell (2017)
	<i>H. elongata</i>	Frankfurters and breakfast sausages	Enhanced hardness and chewiness	Lopez-Lopez, Cofrades, Ruiz-Capillas, & Jimenez-Colmenero (2009)
	Seaweeds <i>L. japonica</i>	Fat reduced pork patties	Improved textural and sensory qualities	Choi et al. (2012)
	Sodium carbonate and inulin	Restructured poultry steaks	Same sensory and textural qualities	Őztürk and Serdaroglu (2017)
	Potassium carbonate	Pork meat	Increased sensory quality	LeMaster et al (2019)
	Ammonium hydroxide (1%)	Brine for beef strip loins	Improved display quality	Parsons et al. (2011a)
Alkaline electrolysed water	Pork loin	Negative textural and sensorial properties	Rigdon et al. (2017a)	

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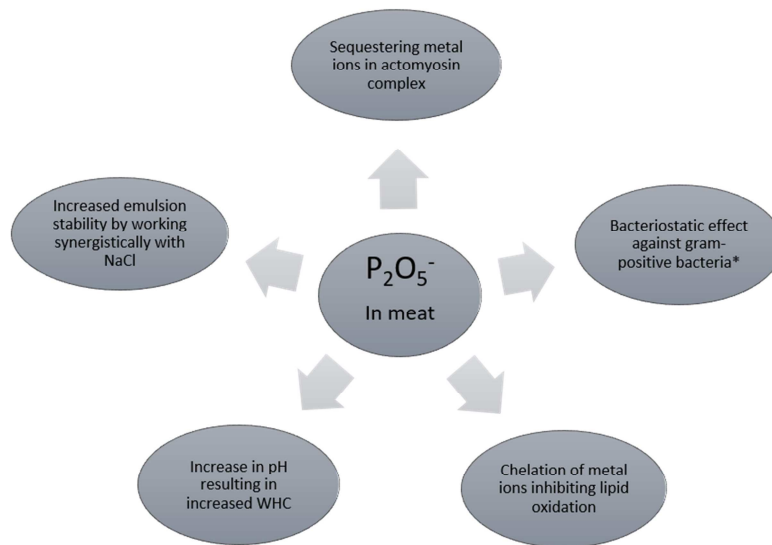


Figure 1. Some important functionalities of phosphates in meat products

*However, the quantities used in meat are not high enough to have a significant bacteriostatic effect.

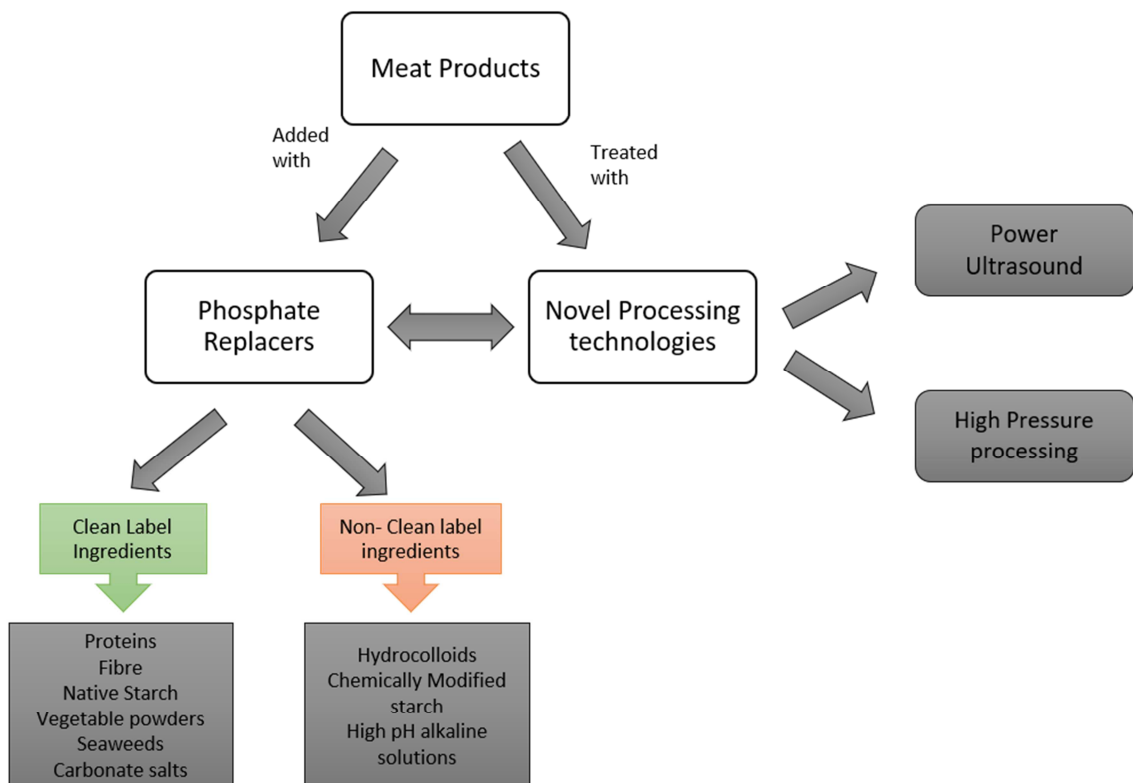


Figure 2. Phosphate replacing strategy in meat products using phosphate replacers and novel processing technology

Highlights:

- Phosphates are highly functional additives in meat products
- Alternative ingredients cannot fully replace the effect of phosphates in meat
- Novel technologies can be combined with ingredients for better functionality in meat
- Power ultrasound can accelerate ingredient diffusion and dispersion in meat
- High pressure processing can improve meat-protein interaction with ingredients

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