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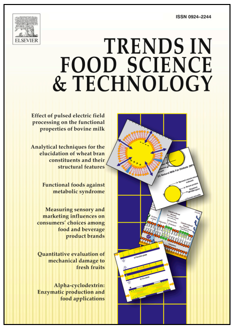

Systematic review of novel processing technologies and ingredients for the reduction of phosphate additives in processed meat

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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.

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

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

1. Introduction

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

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

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

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

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

Various attempts have been made to replace phosphates in meat with suitable ingredients like starches, proteins, seaweeds, hydrocolloids and fibres (Younis & Ahmad, 2015;Resconi, Keenan, Barahona, et al., 2016a). However, the complete replacement of phosphate in meat with alternative ingredients may have negative effects on appearance, texture and other major product characteristics. For example, use of rice starch as a phosphate replacer in whole muscle cooked hams affected the appearance and sensory qualities of meat (Resconi, Keenan, Barahona, et al., 2016a). Similar results were obtained when the amount of phosphate added to meat was reduced without adding any functional ingredients (Glorieux, Goemaere, Steen, & Fraeye, 2017). Studies have shown that alternative technologies can be effective in enhancing the quality of meat processed with added alternative ingredients. Among the technologies, high pressure processing (HPP) proved to be effective in improving the functionality of meat products by altering the meat structure. The application of HPP in meat products can modify the protein spatial structure resulting in solubilisation of myofibrillar proteins. This can reduce the quantities of salts and phosphates required in processed meat (Tamm, Bolumar, Bajovic, & Toepfl, 2016). For example, reduced-salt cooked ham was produced without any changes in WHC and texture using a salt replacer (KCl) and HPP at 100 MPa (Tamm, Bolumar, Bajovic, & Toepfl, 2016). Similarly, ultrasound (US) technology has been widely used to assist effective ingredient distribution and diffusion within food matrices. For example, US has been shown to accelerate the diffusion of salt (McDonnell, Allen, Duane, Morin, Casey, & Lyng, 2017) and salt replacers in pork tissue (Ojha, Keenan, Bright, Kerry, & Tiwari, 2016).

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

2. Phosphates in Processed Meat

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

2.1. Types of Phosphates Used in Meat

Several forms of molecular forms of phosphate (P_2O_5) exist and they are selected depending on their required function in the food matrix. Phosphates are classified according to the number of phosphorus atoms sharing oxygen atoms (Lampila & Godber, 2002). They are as ortho- or monophosphates with one phosphate molecule, di- or pyrophosphates with two phosphate molecules, triphosphates with three phosphate molecules and polyphosphates with more than three phosphates molecules. The molecular structures of phosphates are ring or metaphosphates, chain /linear phosphates or ultra /branched phosphate structures with a combination of ring and linear phosphates.

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

2.2. Functionality of phosphates in meat

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

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

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

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

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

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

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

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

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

3. Strategies to reduce phosphates in meat products

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

3.1 Ingredient strategies for phosphate reduction in processed meat

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

3.1.1. Water-binding and emulsifying properties

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

(*Penaeus vannamei*). The shrimps were treated with sodium bicarbonate ($NaHCO_3$), lysine and sodium bicarbonate – lysine mixture at various concentrations and frozen. Results of thawing yield, cooking yield, colour, textural values were compared with those of sodium tri polyphosphates (STPP) treated shrimps. It was concluded that the shrimps treated with $NaHCO_3$ /lysine each at 1% (w/v) improved the water holding capacity and cooking yield (100.45%, w/w) similar to that of STPP treated samples (101.73%, w/w), proving that $NaHCO_3$ can act as a possible phosphate replacer. In a study by Casco et al. (2013), SavorPhos - mixture of citrus flour that is rich in fibre content, all-natural flavourings and less than 2% sodium carbonate is used as phosphate replacer in water and oil-based marinades in rotisserie birds and boneless-skinless breast. SavorPhos when used in water marinade resulted in equal performance in WHC and cook loss as that of control phosphate blend whereas when used in oil marinade, it increased WHC and decreased cook loss. The study of Bertram, Meyer, Wu, Zhou, & Andersen (2008) elucidated to the structural changes induced by sodium bicarbonate ($NaHCO_3$), salt (NaCl) and tetrasodium pyrophosphate ($Na_4O_7P_2$) in enhanced pork by use of low-field nuclear magnetic resonance and confocal laser scanning microscopy. It was found that sodium bicarbonate ($NaHCO_3$) resulted in increased solubilisation of proteins and a higher degree of swelling of the myofibril, resulting in increased yield and reduced cooking loss (Bertram et al., 2008).

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

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

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

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

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

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

3.1.3. Colour and oxidative stability

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

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

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

3.2 Processing technologies for phosphate reduction in processed meat

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

3.2.1 Power Ultrasound

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

3.2.1.1. Water-binding and ingredient distribution properties

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

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

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

3.2.1.2. Texture/sensory properties

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

3.2.1.3. Oxidative stability

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

4.2. High Pressure Processing

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

3.2.2.1. Water-binding properties

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

3.2.2.1. Texture and sensory properties

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

3.2.2.3. Colour and oxidative stability

The study of Fuentes et al., (2010) showed that application of high hydrostatic pressure of 600 MPa for 6 minutes increased the lipid and protein oxidation in vacuum packaged Iberian dry cured ham. Similar increase in the protein and lipid oxidation were obtained when high pressure of 600 MPa was applied to the cooked and raw ground beef for 5 minutes (Jung et al., 2013). Other disadvantages of HPP are a reduction in sensory properties due to the resistance offered by food enzymes and pressure resistant bacterial spores resulting in spoilage of food (Inguglia et al., 2017). This highlights the importance of optimisation processes which is suitable for processing parameters.

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

5. Conclusion (Future Trends)

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

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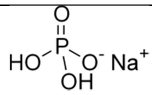
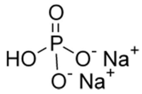
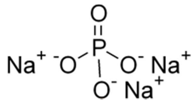
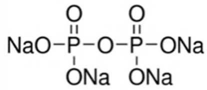
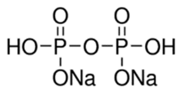
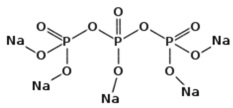
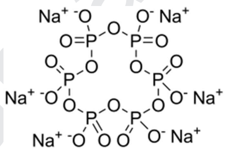
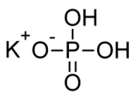
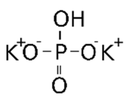
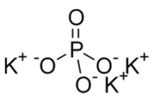
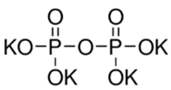
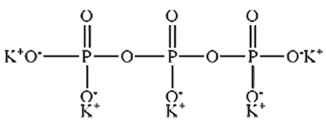
Table 1. List of phosphates used in meat products with corresponding P_2O_5 content adapted from Nguyen et al. (2011) and Lampila & McMillin (2017)

Common names	Chemical structure	pH (1% solution)	P_2O_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.

Table 2 List of different ingredients that can 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 *H. elongata*	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 Agaricusbisporus	Meat emulsion batters	Increase in emulsion stability	Kurt & Genccelep (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)
	H. elongata	Frankfurters and breakfast sausages	Enhanced hardness and chewiness	Lopez-Lopez, Cofrades, Ruiz-Capillas, & Jimenez-Colmenero (2009)
	Seaweeds *L. japonica*	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	Őztűrk and Serdaroğlu (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)

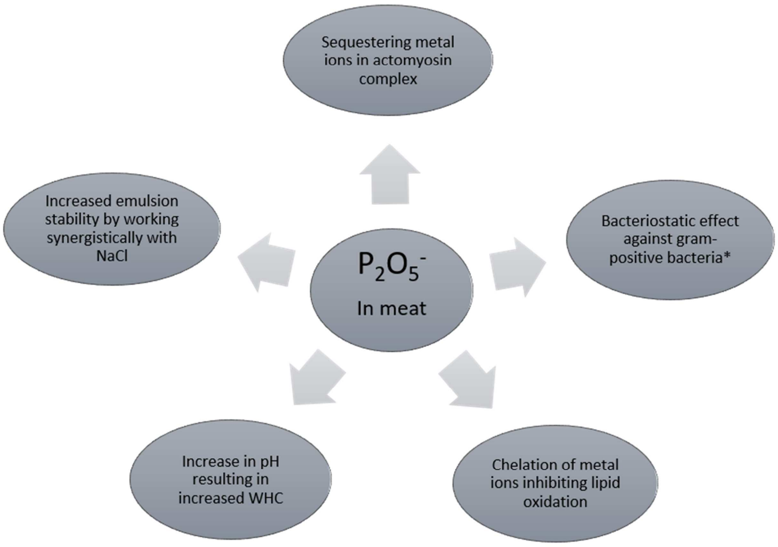


Figure 1. Some important functionalities of phosphates in meat products

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

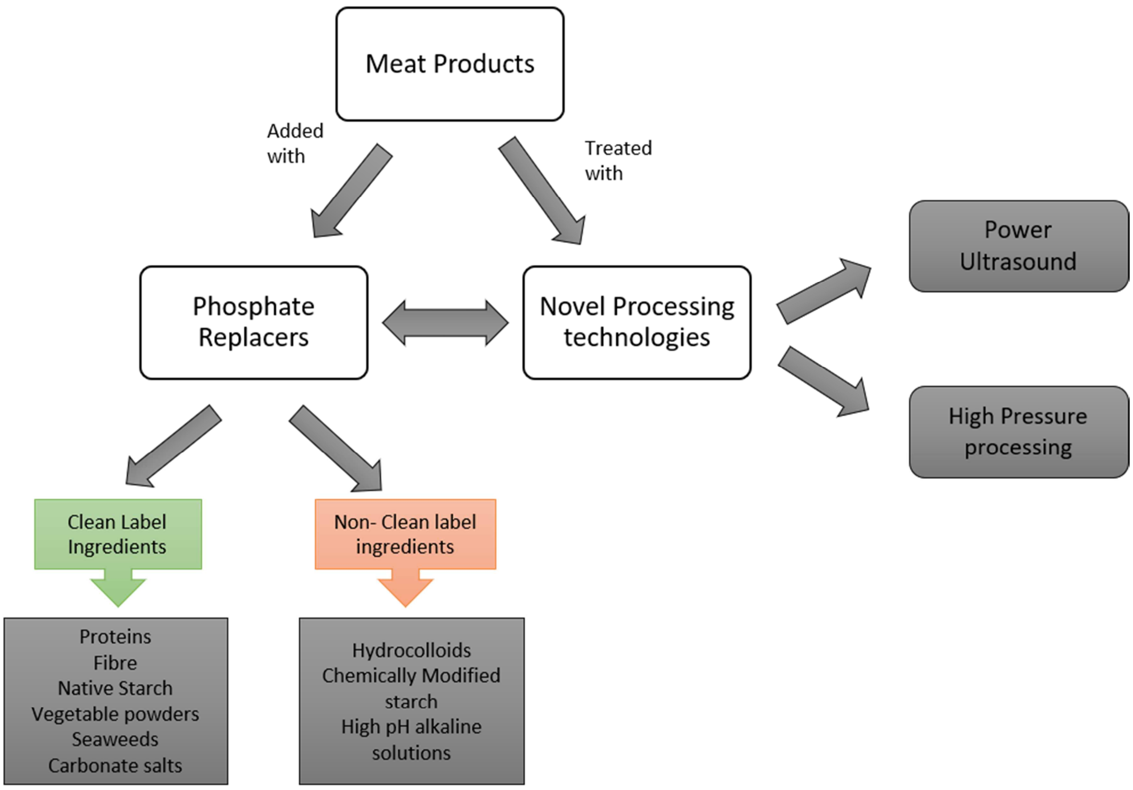


Figure 2. Phosphate replacing strategy in meat products using phosphate replacers and novel processing technology

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