Antibacterial efficacy of phosvitin, carvacrol, or nisin alone or combined against foodborne human enteric pathogens

by

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ABSTRACT

Natural antimicrobials, from plant, animal or microbial sources, have good potential for use as preservative systems to improve food safety, extend shelf life and enhance the overall quality of food products, while promoting the image of “healthier” foods. The overall objective of this research was to evaluate the antimicrobial efficacy of phosvitin alone or combined with carvacrol or nisin against four human enteric foodborne pathogens. Growth inhibition of *Salmonella enterica*, *Listeria monocytogenes*, *Escherichia coli O157:H7* or *Staphylococcus aureus* by the antimicrobials used singly or in combination in brain heart infusion (BHI) broth (35 °C, 24 hours) was evaluated using a Bioscreen C turbidometer (OD 600nm). Subsequently, selected concentrations of the antimicrobials were evaluated for their effectiveness in controlling growth of the pathogens and background microflora in onion mushroom soup at 12 °C and 35 °C. Additional experiments involving UV spectroscopy and transmission electron microscopy (TEM) were performed to investigate the antibacterial mechanism of action of carvacrol in *E. coli O157:H7* and *L. monocytogenes* Scott A. In BHI broth the minimum inhibitory concentration (MIC) of phosvitin and carvacrol was 80 mg/ml and 0.14 mg/ml, respectively, for both *S. enterica* and *L. monocytogenes*. The MIC of phosvitin and carvacrol was greater than 100 mg/ml and 0.12 mg/ml, respectively (for *S. aureus*) and 80 mg/ml and 0.12 mg/ml, respectively, for *E. coli*. In onion mushroom soup, the combination of phosvitin (60 mg/ml) and carvacrol (0.40 mg/ml) exerted the greatest cidal effect throughout storage against all foodborne pathogens tested. Irrespective of storage temperature (12 °C or 35 °C), phosvitin combined with nisin did not offer enhanced antibacterial effect above that provided by phosvitin used alone. For all organisms, leakage
of $A_{260}$ absorbing material from the bacterial cells increased significantly with increased carvacrol concentration and exposure time. There was a very strong correlation between the initial rate of release of $A_{260}$ material and death rate of the pathogens ($r = 0.998$). At 0.4 mg/ml carvacrol, *E. coli* O157:H7 cells appeared collapsed and showed signs of lysis when observed by TEM. At 0.4 and 0.6 mg/ml carvacrol, *L. monocytogenes* cells showed no apparent physical damage (distortion of cell shape) despite substantial loss of viability; however, exudation of intracellular material was detected by UV spectroscopy and TEM photographs of negatively stained cells.

Based on results of the present studies it is concluded that: i) use of phosvitin and carvacrol in combination has good potential for controlling growth of foodborne pathogenic bacteria in onion mushroom soup and ensuring the microbial safety of this potentially hazardous food product, ii) phosvitin/nisin combinations are far less effective for inhibiting growth of pathogens in soup, iii) death of bacterial cells exposed to carvacrol involves damage to the cytoplasmic membrane.
CHAPTER 1. GENERAL INTRODUCTION

Introduction

Bacterial pathogens present in food and beverages can infect humans and cause foodborne illnesses. The World Health Organization estimates that 1.8 million people died in the world in 2005 due to foodborne related illnesses. The Center for Disease Control and Prevention estimated that foodborne diseases causes approximately 76 million illnesses, 325,000 hospitalizations and 5000 deaths in the United States each year (Mead et al., 1999). Based on recent epidemiological data, there has been a decrease in the incidence of foodborne disease (9.4 illnesses), hospitalizations (55,961) and deaths (1,351) annually (Scallan et al., 2011). The US cost of foodborne illness associated with Campylobacter jejuni, Clostridium perfringens, Escherichia coli O157:H7, Listeria monocytogenes, Salmonella, Staphylococcus aureus and Toxoplasma gondii is between $6.5 and $34.9 billion (Buzby and Roberts, 1997). Total elimination of bacterial pathogens is virtually impossible so government, food manufacturers, processors and retailers try to ensure that foodborne diseases are minimized for consumers.

The increased usage of foods formulated with chemical preservatives has raised consumer health concerns and created a demand for more “natural” and minimally processed foods. As a result, there has been a great interest in naturally produced antimicrobial agents to replace chemically synthetic preservatives such as nitrates, benzoates, sulphites, sorbates, salt and ethylenediaminetetraacetic acid. The insistence for more natural antimicrobials has driven the trend towards “Green Consumerism”. “Green” antimicrobials should possess the
following attributes: 1) low mammalian toxicity/cytotoxicity, 2) low skin sensitization potential, 3) low eco-toxicity, 4) low bioaccumulation potential, 5) low emission potential during manufacture, application or post application, 6) no or low volatile organic compound (VOC) content, as applicable, and 7) complete effectiveness against the relevant target organisms (Sofos, 1998; Kruger and Mann, 2003; Shrankel, 2004; Davidson et al., 2005; Smith, et al., 2005; Rulis, 2009). Natural antimicrobials have good potential for use as preservative systems to improve food safety, extend shelf life and improve the overall quality of food products, while promoting the image of “healthier” foods. In order for the food industry to fully make the change from the use of synthetic sources to purely natural sources research must address, the limits of antimicrobial activity, the overall cost, the most effective concentration, optimization of the antimicrobial, use of hurdle technology and address regulatory concerns.

The food industry is addressing the issue by gradually incorporating natural antimicrobials from, plant, animal or microbial sources into food products to replace the more traditionally used synthetic chemical preservatives. Poultry eggs contain many proteins that have antimicrobial functions and phosvitin, a major egg yolk protein, is a highly phosphorylated protein that has the ability to bond with metal cations (Khan et al., 2000). The ability to bind metal cations deprives the environment of essential nutrients and possibly interacts with the membranes of foodborne pathogens. It is this property which could theoretically make it a candidate for uses as a natural antimicrobial. Carvacrol, an essential oil from oregano and thyme, is a phenolic compound that has been shown to have antimicrobial activity. It is believed to exert antimicrobial activity by disrupting the
cytoplasmic membrane of foodborne pathogens. In some instances the high concentration needed for it to be effective as an antimicrobial would not be organoleptically pleasing to consumers. Therefore, efforts need to be made to use plant essential oil such as carvacrol in very low amounts that would be effective in controlling microorganisms while not contributing an overwhelming flavor and/or odor notes to food products. One approach to achieve this type of application is by combining low levels of the essential oil with an antimicrobial to get the desired result. Nisin, produced by *Lactococcus lactis* *spp lactis*, is the only approved bacteriocin used in food. It is primarily active against Gram-positive bacteria by causing pores in the cell membrane, resulting in leakage of cytoplasmic constituents. Generally, food applications of nisin can be expensive based on the quantities needed for antimicrobial efficacy. In addition, nisin has little or no effect on Gram-negative bacteria except in instance when a membrane destabilizing agent such as EDTA is used in combination with this bacteriocin. It is hypothesized that the antimicrobial efficacy of nisin against Gram-negative bacteria is enhanced when this bacteriocin is combined with phosvitin.

Properties of these three sources of natural antimicrobials can be used to improve microbial safety of foods. Combining these natural antimicrobials could possibly increase the effectiveness of the antimicrobials proving to be better than if they were used alone against foodborne pathogens. Synergistic or additive effects between the antimicrobials may permit the use of relatively low amounts of each antimicrobial and thereby reduce cost of the antimicrobial treatment while improving the antimicrobial efficiency.
The first objective was to evaluate and establish the minimum inhibitory concentration (MIC) of selected antimicrobials in laboratory broth medium against various foodborne pathogens. The second objective was to determine the antimicrobial efficacy of phosvitin, carvacrol and nisin alone or phosvitin/carvacrol combination or phosvitin/nisin combination against the various human enteric pathogens *Escherichia coli* O157:H7, *Salmonella enterica*, *Listeria monocytogenes*, and *Staphylococcus aureus* in a food product. After determining the antimicrobial efficacy it was important to establish the possible mechanism of action of carvacrol correlated to death and the effect of this natural antimicrobial on the extent of sub-lethal injury in populations of foodborne human enteric pathogens that survive exposure to carvacrol.

**Dissertation Organization**

This dissertation is organized into seven chapters. The first chapter is a general introduction. The second chapter is a general literature review that contains information relevant to the research performed (Chapters 3-6) followed by a general conclusion. The seventh and final chapter provides a general summary of the research described. All pertinent tables, figures and graphs appear at the end their respective paper, which follows a specified journal format. References can be found at the conclusion of each chapter with formatting following journal specifications. It is the intent that Chapter 3 be submitted to the Journal of Food Protection, Chapter 4 Journal of Food Science, Chapter 5 International Journal of Food Microbiolgy, and Chapter 6 Journal of Food Protection. The following papers entitled “Antimicrobial efficacy of phosvitin alone or combined with nisin against
Listeria monocytogenes in a laboratory broth medium at 35 °C” and “Control of Salmonella enterica and Staphylococcus aureus in a laboratory medium and a commercial-type soup using phosvitin, carvacrol, or combinations” were presented at the annual meeting of the International Association of Food Protection in Anaheim, CA (August 2010), and Madison, WI (2011), respectively. Lastly, paper entitled “Antimicrobial efficacy of phosvitin, nisin, and combinations against Salmonella enterica in a laboratory medium and a commercial-type soup” will be presented at the annual meeting of the Institute of Food Technologists in New Orleans, LA (June 2011).
CHAPTER 2. LITERATURE REVIEW

Phosvitin

Composition

Phosvitin is a phosphoglycoprotein that was first isolated in 1949 by Mecham and Olcott. It is made from vitellogenin (produced in the liver) and is found exclusively in the granule fraction of chicken egg yolk (Wallace and Morgan, 1986) in which it represents 4% of egg yolk dry matter. Phosvitin has a molecular weight of 35 kDa and contains 10% phosphorus (80% of total yolk phosphorus), 12.3% nitrogen, and 6.5% carbohydrate (Renugopalakrishnan, 1985; Burley and Vadhera, 1989; Xu et al., 2007). It is the major protein component in egg yolk and is currently known as the most phosphorylated protein in nature. Phosvitin has an amino acid sequence containing 217 amino acids of which 123 are serines, with 90% of them being phosphorylated (Fig. 1; Taborsky, 1983; Byrne et al., 1984; Clark, 1985). This distinct, polyanionic, highly phosphorylated protein, contains 56% serine residues, 15% basic and 10% acidic amino acid residues (Taborsky, 1963; Taborsky and Mok, 1967; Byrne et al., 1984; Losso, 1994; Xu et al., 2007). Its unique amino acid sequence leads to the structure and properties of phosvitin.

Figure 1. Amino acid sequence of hen egg yolk phosvitin. Adapted from Byrne et al. 1984; Clark 1985).

Extraction and isolation/purification

Phosvitin was first isolated in 1949 by Mecham and Olcott and the methods described by those researchers are most commonly used for extraction and isolation. Sigma Chemical Co. uses another method described by Sundararajan et al., 1960 for extraction and isolation of phosvitin. The current issue with previously used methods for preparation, extraction and isolation (size-exclusion, anion-exchange chromatography, hydrophobic-interaction chromatography, gel electrophoresis) is that chemicals used are not food-grade or non-aqueous (Wallace and Morgan, 1986; Castellani et al., 2003) limiting use of the methods for production of foodgrade phosvitin. Choi et al., (2005) were able to successfully purify egg yolks by a sodium chloride method. Tedious extraction and purification methods for phosvitin are largely responsible for the relatively high cost of this glycoprotein. The cost of phosvitin is $1130.00 per gram based on current price listed in the Sigma 2011 catalog. More recently, researchers at Iowa State University developed a water/ethanol-based method that permits an efficient cost-effective way of extracting and purifying phosvitin from yolks of hens’ eggs. Varying yield of final product, purity and polypeptide composition (Table 1; Castellani et al., 2003) were also a concern.

Table 1. Amino acid composition (mol %) of phosvitin sequences from the literature.

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Purified a</th>
<th>Seq I b</th>
<th>Seq II c</th>
<th>Amino Acid</th>
<th>Purified a</th>
<th>Seq I b</th>
<th>Seq II c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asx</td>
<td>7.0</td>
<td>6.4</td>
<td>6.0</td>
<td>Tyr</td>
<td>0.6</td>
<td>1.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Glx</td>
<td>7.2</td>
<td>7.6</td>
<td>5.0</td>
<td>Val</td>
<td>1.9</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Ser</td>
<td>47.1</td>
<td>48.8</td>
<td>57.0</td>
<td>Met</td>
<td>0.6</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Gly</td>
<td>3.9</td>
<td>3.2</td>
<td>2.3</td>
<td>Cys</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>His</td>
<td>5.5</td>
<td>4.0</td>
<td>6.0</td>
<td>Ile</td>
<td>1.1</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Arg</td>
<td>5.5</td>
<td>6.3</td>
<td>5.1</td>
<td>Leu</td>
<td>1.6</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Thr</td>
<td>2.3</td>
<td>4.0</td>
<td>1.8</td>
<td>Phe</td>
<td>1.0</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Ala</td>
<td>4.1</td>
<td>3.2</td>
<td>3.2</td>
<td>Lys</td>
<td>8.7</td>
<td>7.1</td>
<td>6.9</td>
</tr>
</tbody>
</table>

aCastellani et al., 2003; bMabuchi et al., 1996; cByrne et al., 1984
**Structure of phosvitin**

Phosvitin is a highly unfolded flexible protein consisting of two polypeptide components, (alpha and beta) (Abe et al., 1982; Itoh et al., 1983; Vogel, 1983). The main factor that influences the structure of phosvitin is pH. At a physiological pH, phosvitin exists in a random coil conformation and at acidic pH the β conformation predominates (Vogul, 1983; Yasui et al., 1989), which influences solubility of this glycoprotein (Table 2; Castellani et al., 2003). Phosvitin is extremely hydrophilic with a proportionately lower amount of hydrophobic side chains (Figure 2), and possesses a net negative charge (Sattar Khan et al., 2000). At physiological pH phosphoserine residues are exposed and can be protonated or deprotonated depending on the chemical characteristics of the solvent (Vogul, 1983). In acidic pH phosphoryl groups can shift from amide to ester linkages; whereas, at alkaline pH free amino groups become masked also causing phosvitin to release acid (Connelly and Taborsky, 1961; Taborsky and Allende, 1962).

**Stability of phosvitin**

Native phosvitin exhibits relatively good stability to heat, pressure and enzyme action. Little or no change in structure or precipitation of this protein occurs at 100°C for several hours, concurrent with varying pH (4 to 8 pH) (Mecham and Olcott, 1949; Matsudomi et al., 2006). Phosvitin is also not affected by high pressures up to 600 MPa (Castellani et al., 2004). Phosvitin is not easily digested by pepsin, trypsin, and chymotrypsin. In fact the core of the protein remains largely intact after enzymatic digestion, due to the negative charge of the phosphate group rendering the neighboring peptide bonds
resistant to proteolytic action (Goulas et al., 1996). Dephosphorylation methods have been employed to enhance digesting phosvitin (Jiang and Mine, 2000, 2001).

Table 2. Solubility of isolated phosvitin at different pH values. Source: Castellani et al., 2003.

<table>
<thead>
<tr>
<th>pH</th>
<th>% of solubility(^a) ± SD(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>9.30 ± 4.2</td>
</tr>
<tr>
<td>2.5</td>
<td>83.5 ± 1.7</td>
</tr>
<tr>
<td>3.6</td>
<td>84.5 ± 1.5</td>
</tr>
<tr>
<td>5.0</td>
<td>90.6 ± 2.5</td>
</tr>
<tr>
<td>7.0</td>
<td>97.7 ± 1.4</td>
</tr>
</tbody>
</table>

\(^a\) Expressed in percent of N from lyophilized isolated protein
\(^b\) Standard deviation

Figure 2. Structural schematic of hen egg yolk phosvitin.

Hen egg yolk phosvitin, amino acid composition and structure provide a variety of functional (metal chelation) and biological properties (antioxidant and antimicrobial). The primary structure of phosvitin makes it one of the strongest metal chelating glycoproteins (Grizzuttiand Permann 1973; Hegenauer et al.; 1979; Castellani et al., 2004; Xu et al., 2007).

Metal chelation

The capacity of phosvitin to chelate metal ions, as well as peptides resulting from enzymatic digestion of this glycoprotein are major factors related on phosvitin’s influence
mineral bioavailability. Avian eggs are rich in iron and about 95% is bound by phosvitin (Greengard et al., 1964). Almost all iron, calcium, and phosphorus are contained in the yolk (Taborsky, 1983; Watkins, 1995). The numerous phosphorylated serine residues have a strong affinity for divalent metals and contribute to the chelating ability of phosvitin (Osaki et al., 1975; Grogan and Taborsky, 1987). Phosvitin contains between 3 to 6 iron atoms per molecule depending on the method of isolation from hens’ eggs; however, it has a binding capacity of about 60 iron molecules (Mecham and Olcott, 1949; Taborsky, 1963; Webb et al., 1973, Albright et al., 1984). The iron binding capacity differs dependent on source of phosvitin, for example phosvitin in fish eggs have a lower iron binding capacity due to less phosphorus and serine content, and smaller size (Table 3; Guerdin-Dubiard et al., 2002). When iron binds with phosvitin an iron-phosvitin complex is formed, rendering phosvitin insoluble and the iron unavailable. Phosvitin oxidizes Fe (II) to Fe(III) and also binds substantial amounts of Fe (III) (Osaki et al., 1975).

Trypsin hydrolyzed phosvitin enhanced Ca-binding capacity and inhibited the formation of insoluble Ca phosphate (Jiang and Mine, 2001). Ishikawa et al 2004 investigated the effect of phosvitin on Fe (II)-catalyzed hydroxyl radical (•OH) formation from H₂O₂ in the Fenton reaction system. Those authors reported that phosvitin accelerated Fe (II) autoxidation thus decreasing availability of Fe (II) participation in the •OH-generating Fenton reaction. Phosvitin was also found to protect DNA against oxidative damage induced by Fe (II) and H₂O₂. These results provide insight into the mechanism of protection of the developing embryo against iron-dependent oxidative damage in ovo. Choi et al., 2005 examined the effects of phosvitin and tryptic digests of phosvitin on the efficiency of enhancing calcium absorption and accumulation in the bones of rats. Calcium absorption
was found to be greater with peptides from tryptic digestion of phosvitin; thus, increasing the bioavailability of Ca and accumulation in bone. Ishikawa et al., 2007 demonstrated that native phosvitin decreased absorption of iron, calcium and magnesium, suggesting that mineral bioavailability is influenced by the following: the type of proteins (amino acid composition), its binding strength to minerals, and resistance to proteolysis.

**Table 3. Iron Binding properties of phosvitins.** Source: Guerin-Dubiard et al., 2002.

<table>
<thead>
<tr>
<th>Phosvitin</th>
<th>MW phosvitin (Da)</th>
<th>Mol Fe/mol Phosvitin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigma</td>
<td>35,000³</td>
<td>36.0</td>
</tr>
<tr>
<td>Laboratory</td>
<td>35,000³</td>
<td>32.0</td>
</tr>
<tr>
<td>*Ling</td>
<td>#23,000³</td>
<td>9.5</td>
</tr>
<tr>
<td>*Siki</td>
<td>#25,000³</td>
<td>3.6</td>
</tr>
</tbody>
</table>

³MW were estimated from SDS-PAGE analysis
¹Ling and Siki are phosvitin from fish

**Antioxidant and nutritional aspects**

Phosvitin plays an important role as an antioxidant in the yolk by inhibiting iron-catalyzed lipid oxidation (Lu and Baker, 1986). Various studies have observed the antioxidant properties of phosvitin and peptides derived from phosvitin; antioxidant potential findings were both negative and positive. Phosvitin is efficient up to a Fe²⁺ to phosvitin ration of 30:1, and pH 6 provides its maximal antioxidant activity (Guerin-Dubiard et al., 2002). Antioxidant ability did not change when phosvitin was pasteurized (61.1 °C); however, autoclaving (121.1 °C, 10 min) phosvitin decreased inhibitory capacity on iron catalysis (Lu and Baker, 1986). Native phosvitin has been considered nutritionally negative, in that it resists proteolytic actions (Goulas et al., 1996) and lowers bioavailability of iron (Morris and Greene, 1972) due to its highly phosphorylated structure. It has been
demonstrated via both *in vitro* and *in vivo* experiments that yolk protein intake resulted in decreased mineral absorption and digestibility of the phosvitin in rats (Ishikawa et al., 2007).

To by-pass the hurdle of low bioavailability of iron, phosvitin has been hydrolyzed to form smaller peptides (1-3kDa) following dephosphorylation (Jiang and Mine, 2000, 2001). The smaller peptides consist of about 35% of the phosphorus content of native phosvitin, indicating that the peptides would be individually less active than native phosvitin (Jiang and Mine, 2001). Ishikawa et al., (2004) found phosvitin and digested phosvitin were more efficient antioxidants in inhibiting •OH formation compared to metal-binding proteins (ferritin, transferrin, lactoferrin, ovotransferrin, and bovine serum albumen), iron chelators (DFO-deferoxamine mesylate, NTA-nitrioloacetic acid, EDTA-ethylenediamine tetraacetate, citrate, ADP, phytate) and hydroxyl radical scavengers (mannitol, thiourea, ethanol, DMSO). The tryptic digested phosvitin was as efficient an antioxidant as phosvitin towards inhibiting Fe (II) catalyzed •OH formation, indicating that both forms have iron-binding ability. Xu et al., 2007 also observed the antioxidant activities of intact phosvitin, and tryptic digests of phosvitin. Those same researchers reported that digested phosvitin was more effective than intact phosvitin at inhibiting lipid oxidation in a linoleic acid system. In addition, the digested form of phosvitin was efficient in radical scavenging activity on 2,2-diphenyl-1-picrylhydrazyl induced free radicals; however, its chelating capabilities were relatively less effective. Antioxidant activity of phosvitin has been demonstrated in egg yolk emulsion as well as meat model systems (Lu and Baker, 1986; Lee et al., 2002). Also phosvitin inhibited lipid peroxidation induced by UV irradiation in a dose-dependent manner in the presence of excess iron (Ishikawa et al., 2005). These results suggest that phosvitin and peptides derived
from phosvitin might be useful for prevention of other iron-mediated oxidative stress related diseases, such as colorectal cancer (Katayama et al., 2006; Ishikawa et al., 2009).

The mechanism of action of digested phosvitin is less understood, and is possibly influenced by peptide composition (histidine, methionine, and tyrosine) (Yamashoji et al., 1979) or structure and not solely on the phosphorus content (native phosvitin postulation) (Hegenauer et al., 1979; Xu et al., 2007). The aforementioned properties, illustrate the possibility of its commercial uses as a natural antioxidant.

**Antimicrobial properties**

The iron binding capabilities contribute to the antimicrobial properties of phosvitin. Iron is an essential element for all living organisms and interestingly, ninety-five percent of iron in hen’s egg yolk is bound by phosvitin in a very strong and stable conformation to avoid being used by microbes (Greengard et al., 1964). To our knowledge there has only been one published study on the antimicrobial potential of phosvitin. Sattar Khan et al., 2000 tested native phosvitin, a protease digested phosvitin fraction and phosvitin-galactomannan conjugate against *Escherichia coli* under thermal stress. These authors reported that at 50 °C for 20 minutes in L-broth, both native phosvitin and phosvitin-galactomannan conjugate were significantly more effective than the control in decreasing the viability of the target organism; whereas, the digested fraction was not effective. It was noted the antimicrobial properties of phosvitin could be reversed by the addition of Ca$^{2+}$ (Table 4) indicating that divalent cations may occupy sites on phosphate groups of phosvitin to prevent further binding of cations important in meeting the nutritional needs of the organism. Antimicrobial activity of intact phosvitin is believed to be due to chelating abilities and surface activity.
(affinity for outer membrane). These activities in conjunction with thermal stress seem to contribute to the loss of viability of *E. coli*  (Sattar Khan et al., 2000).

### Table 4. Determination of Calcium Binding Capacity of 0.1% Native and Modified Phosvitins. Source: Sattar Khan et al., 2000.

<table>
<thead>
<tr>
<th>Samples</th>
<th>bound calcium (mol/mol of phosvitin)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at pH 3.6</td>
</tr>
<tr>
<td>Native phosvitin <em>a</em></td>
<td>0</td>
</tr>
<tr>
<td>Native phosvitin</td>
<td>20</td>
</tr>
<tr>
<td>Phosvitin-galactomannan conjugate</td>
<td>27</td>
</tr>
<tr>
<td>α-chymotrypsin-digested phosvitin</td>
<td>17</td>
</tr>
</tbody>
</table>

*a*Phosvitin without calcium

**Plant-derived sources of antimicrobials**

The growing number of foodborne illness-related outbreaks due to human enteric pathogens is an increasing concern to regulatory agencies, the food industry, and consumers. While effective control of foodborne pathogens is crucial to ensuring microbial food safety, methods of control involving synthetic chemical preservatives are becoming less desirable to consumers. This consumer attitude is part of a growing trend towards “Green Consumerism” emphasizing the reduction or elimination of preservative agents such as nitrite and sodium chloride from foods (Burt, 2004) and encouraging the use of herbs and spices with antimicrobial properties to preserve foods, promote healthier foods and improve food safety.

Herbs and spices have been used for centuries specifically for medicinal purposes, flavor, fragrances, and as natural preservative methods for a variety of foods (Achinewhu et al., 1995; Cowan, 1999). The majority of essential oils are classified as Generally
Recognized As Safe (GRAS). From a food safety standpoint, the antimicrobial properties possessed by the essential oil components of herbs and spices have only been scientifically confirmed within the last 30 years (Olasupo et al., 2004). The phenolic compounds in the essential oil fraction of the plant possess antimicrobial properties (Beuchat, 1994). There have been numerous studies published addressing the antimicrobial properties of a wide variety of essential oils (Remmal et al., 1993; Hammer et al., 1999; Dorman and Deans, 2000; Frieman et al., 2002; Burt, 2004). Limitations to applications of essential oils as antimicrobial agents are mainly due to intense flavors and odors that effective antimicrobial concentrations may add to foods. One approach that has been deemed useful is to determine the minimum inhibitory concentration (MIC) and apply the essential oil in combination with other antimicrobials or preservative methods to control foodborne pathogens. Such an approach aims to take advantage of additive or synergistic effects of antimicrobial interventions.

**Carvacrol**

**Source and structure**

Carvacrol, an essential oil, is found in the leaves and flowering plant of both thyme (*Thymus vulgaris*) and oregano (*Origanum vulgare*) (Burt, 2004; Oussalah, 2007). The percent composition of carvacrol in oregano ranges from trace amounts to 82% and 2 to 45% in thyme (Lagouri et al., 1993; Arrebola et al., 1994; Burt, 2004). Carvacrol [2-methyl-5-(1-methylethyl) phenol] (Figure 3) is biosynthesized from p-cymene and g-terpinene (Poulose and Croteau, 1978). The hydrophobic phenolic compound in its structure is thought to be the
main contributor to its antimicrobial properties; however, other components of its structure may be also important in this regard (Veldhuizen et al., 2006).

![Carvacrol](image)

**Figure 3. Structure of carvacrol - 1 [2-methyl-5-(1-methylethyl) phenol].**

**Antimicrobial activity**

Several studies have demonstrated that carvacrol has both bacteriostatic and bactericidal activity against microorganisms: *Listeria monocytogenes* (Pol and Smid, 1999; Karatzas et al., 2001, Friedman et al., 2002; Periago et al., 2004; Gaysinsky et al., 2005; Oussalah et al., 2006, Veldhuizen et al., 2007; Solomakos et al., 2008; Perez-Conesa et al., 2011), *Bacillus cereus* (Pol 1999; Ultee et al., 1998, 1999, 2000 a, b; Ultee and Smid, 2001), *Escherichia coli O157:H7* (Helander et al., 1998; Friedman et al., 2002, 2004; Lacroix et al., 2004; Gaysinsky et al., 2005; Kisko and Roller, 2005; Oussalah et al., 2006; Juneja and Friedman 2008; Xu, 2008; Obaidat and Frank, 2009; Pei et al., 2009; Perez-Conessa et al., 2011), *Staphylococcus aureus* (Knowles et al., 2005; Lambert et al., 2001; Oussalah et al., 2006, 2007), *Salmonella enterica* (Helander, 1998, Lacroix, 2004, Friedman et al., 2004; Knowles et al., 2005; Nazer et al., 2005; Zhou et al., 2007; Ravishankar et al., 2010), *Campylobacter jejuni* (Friedman et al., 2002), *Clostridium perfringens* (Juneja and Friedman, 2007), *Pseudomonas fluorescens* (Lambert et al., 2001, Arfa et al., 2006; Di Pasqua et al.,
2006), *Lactobacillus plantarum* (Arfa et al., 2006), *Saccharomyces cerevisiae* (Chami et al., 2005, Arfa et al., 2006), *Botrytis cinerea* (Arfa et al., 2006), *Shigella spp* (Bagamboula et al., 2004) and *Candida albicans* (Chami et al., 2005). The minimum inhibitory concentrations of carvacrol for some foodborne pathogenic bacteria are shown in Table 5.

**Table 5. Minimum inhibitory concentration of carvacrol tested in vitro against selected foodborne pathogens.** Adapted from Burt, 2004.

<table>
<thead>
<tr>
<th>Foodborne Pathogen</th>
<th>Minimum Inhibitory Concentration (MIC) range (ppm)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Escherichia coli</em></td>
<td>225 – 5000</td>
<td>Kim et al., 1995a; Cosentino et al 1999; Pei et al., 2009</td>
</tr>
<tr>
<td><em>Salmonella typhymurium</em></td>
<td>150 – 250</td>
<td>Kim et al., 1995a; Cosentino et al., 1999; Nazer et al 2005</td>
</tr>
<tr>
<td><em>Staphylococcus aureus</em></td>
<td>175 – 450</td>
<td>Cosentino et al., 1999, Lambert et al., 2001</td>
</tr>
<tr>
<td><em>Listeria monocytogenes</em></td>
<td>375 – 5000</td>
<td>Kim et al., 1995a; Cosentino et al 1999; Pol and Smid, 1999</td>
</tr>
<tr>
<td><em>Bacillus cereus</em></td>
<td>187.5 – 900</td>
<td>Cosentino et al., 1999; Pol and Smid, 1999</td>
</tr>
</tbody>
</table>

Carvacrol has been studied extensively in broth model systems as well as the following foods: cheese (Smith-Palmer et al., 2001), apple cider (Friedman et al., 2004, Kisko and Roller 2005), fruit (kiwi and melon) (Roller and Seedhar, 2002), carrot broth (Valero and Salmeron, 2003), salad (Koutsoumanis et al., 1999), lettuce and spinach leaves (Obaidat and Frank, 2009), rice (Ultee et al., 2000b), turkey (Juneja and Friedman, 2007), meat (Veldjuizen et al., 2007, Juneja and Friedman, 2008; Solomakos et al., 2008, Friedman et al., 2009), fish/seafood (Kim et al., 1995; Meljlholm and Dalgaard, 2002; Ravishankar et al.,
Like other antimicrobials there are several factors that influence the efficacy of carvacrol as a natural antimicrobial with concentration being the most important factor. When carvacrol is present at non-lethal concentrations (0.4mM) *Bacillus cereus* can adapt to carvarol at 30°C in growth medium (Ultee et al., 2000a).

Carvacrol has been combined with other preservatives or preservative methods to control foodborne microorganisms. It has been shown to have stronger antimicrobial effect with increased temperature and storage time, and at a lower pH (Burt 2004, Friedman et al., 2004). Some antimicrobials that have been combined with carvacrol to control foodborne microorganisms include p-cymene (Periago et al., 2004; Kisko and Roller, 2005), nisin (Pol and Smid, 1999; Olasupo 2004; Solomakos, 2008), thymol (Nazer et al., 2005, Zhou et al., 2007; Pei et al., 2009), eugenol (Nazar et al., 2005; Pei et al., 2009), citral (Nazer et al., 2005), cinnamaldehyde (Zhou, 2007b) and EDTA (Zhou, 2007a). Encapsulated carvacrol in surfactant micelles has been proven effective in inhibiting growth of *Escherichia coli O157:H7* and *Listeria monocytogenes* (Gaysinsky et al., 2005; Perez-Conessa et al., 2011). Karatzas et al., 2001 reported that carvacrol and high hydrostatic pressure (HPP) acted synergistically in inactivating *Listeria monocytogenes*.

**Mode of action**

The effectiveness of carvacrol as a natural antimicrobial is well established; however, the mechanism of action is less understood and is believed to be associated with damage to the cell membrane. The phenolic component of carvacrol has prompted research focused on its effect on structural and functional damage to cellular membranes (Sikkema et al., 1995, Sivropoulou et al., 1996, Ultee et al., 1999). Permeability of the cell membrane is dependent
on the hydrophobicity of the solutes that have to cross the membrane and the composition (Sikkema et al., 1995). Several methods have been used to investigate the antibacterial mechanism of action of carvacrol: spectrofluorometry (Ultee et al., 1999, 2002; Lambert, 2001), scanning electron microscopy (Kwon et al., 2003; Di Pasqua et al., 2007), confocal laser scanning microscopy (Gill and Holly, 2006) and flow cytometry (Xu et al., 2008). Results of those studies suggest that the antimicrobial mechanism of action of carvacrol is linked to alterations of cellular membranes.

Lambert et al. (2001) determined that the addition of low levels of carvacrol (6.7 mM) against *Psuedomonas aeruginosa* and *Staphylococcus aureus* increased permeability of cells to nuclear stain ethylene bromide, dissipated pH gradients and caused leakage of inorganic ions. Arfa et al., 2006 investigated the relationship between the chemical structure of carvacrol, and carvacrol derivatives (carvacrol methyl ether and carvacryl acetate) against *Escherichia coli, Pseudomonas fluorescens, Staphylococcus aureus, Lactobacillus plantarum, Bacillus subtilis, Saccharomyces cerevisiae* and *Botrytis cinerea*. The carvacrol derivatives were not effective antimicrobials and indicated the importance of the free hydroxyl group in antimicrobial activity of carvacrol. Carvacrol’s hydrogen bonding ability and proton releasing ability caused cell death due to membrane modification; however, this was not seen with carvacrol derivatives. Carvacrol caused a rapid decline in cellular ATP and corresponding increase in extracellular ATP of glucose energized *Bacillus cereus* (Ultee et al 1999), *Escherichia coli* (Helander et al., 1998, Fitzgerald et al., 2004), *Listeria innocua* (Fitzgerald et al., 2004) and *Salmonella typhimurium*. Ultee et al. (2002) proposed that carvacrol also acts as a proton exchanger, by exchanging its hydroxyl proton for another ion such as potassium. Xu et al. (2008) concluded that carvacrol damages the cellular membrane
and reported that flow cytometry could be used to determine other targets (sensitive sites) to elucidate the true underlying antimicrobial effect of carvacrol. *Saccharomyces cerevisiae* membrane was damaged by oregano essential oil which contains carvacrol (Chami et al., 2005). Damage to the cell membrane of that yeast was shown by the release of substances absorbing at 260 nm, as well as by scanning electron microscopy. Gill and Holly (2006) demonstrated that carvacrol inhibited motility, disrupted the cytoplasmic membrane and inhibited ATPase activity in both *Escherichia coli* and *Listeria monocytogenes*. They also suggested that membrane disruption may be a secondary effect rather than the primary effect. Analysis of lipid profiles of bacterial cells (*Escherichia coli* O157:H7, *Staphylococcus aureus*, *Salmonella Typhimurium*, *Pseudomonas fluorescens*, and *Brochothrix thermosphacta*) by gas chromatography showed a decrease of unsaturated fatty acids, particularly C18:2 trans and C18:3 cis after being exposed to carvacrol (Di Pasqua et al., 2007). Those same authors attributed that decrease in unsaturated fatty acids to membrane alterations noticed in scanning electron microscope images.

**Nisin**

There are several published reviews on nisin (Hurst, 1981; Ray, 1992; Hurst and Hoover, 1993; Delves-Broughton and Gasson, 1994; Delves-Broughton et al., 1996; Wessels et al., 1998; Thomas et al. 2000; Abee and Delves-Broughton, 2003; Juncioni de Arouz et al., 2009; Chu et al., 2010). Accordingly, this writing is not intended to be a comprehensive review on nisin but will briefly discuss source, composition and structure, antimicrobial activity, and mode of action of this bacteriocin.

**Source**
Nisin, a bacteriocin, was first discovered in England 1928 by Rogers and Whittier. It is produced as a defense response to some lactic acid bacteria (LAB), specifically *Lactococcus lactis* subspecies *lactis* (Juncioni de Arouz et al., 2009). The use of nisin as a suitable food preservative was first demonstrated by Hirsch et al. in 1951. To date, nisin is the only Generally Recognized As Safe (GRAS) commercially available bacteriocin approved for use as a preservative additive in over fifty countries (FAO/WHO, 1969; FDA, 1988; Jay, 2000). Nisin can be made synthetically (Fukase et al., 1988) or naturally produced from culture fluids or cells of the originating organism during fermentation of a modified milk medium (Cheeseman and Berridge, 1957; Bailey and Hurst, 1971; Lee and Kim, 1985). Nisaplin® (produced by Danisco) and Chrisin are commercial fermentates prepared by using wild-type isolates of *Lac. lactis* subsp. *lactis*.

**Composition and structure**

Nisin is a categorized as a Class I lantibiotic. It is a small cationic, amphophilic polypeptide containing lanthionine and methyllanthione groups (Klaenhammer, 1993). It is very flexible in structure and normally present in the more stable dimer form. The monomer of nisin has a molecular weight of 3.5 kDa and contains 34 amino acids residues. There are two forms of nisin produced, A (Figure 4) and Z. The two forms differ only by the number of histidines present; form A has two and Z has one. In variant Z the histidine at position 27 is exchanged for asparagine, thus increasing its solubility and diffusion characteristics of nisin (Mulders et al., 1991; De Vos et al., 1993; Laridie et al., 2003). The unusual amino acids are thought to be responsible for the functional properties of nisin (ex. acid tolerance,

Figure 4. Structure of nisin form A. ABU, aminobutyric acid; DHA, dehydroalanine; DHB, dehydrobutyrine (β-methyldehydroalanine); ALA-S-ALA, lanthionine; ABU-S-ALA, β-methyllanthionine. Source: Gross and Morrell, 1971.

Antimicrobial spectrum

Nisin has been used as a natural antimicrobial peptide and is effective against gram positive bacteria, including its producer organism. The sensitivity of vegetative cells and spores to nisin may vary between strains within the same species of the following Genera of bacteria: Alicyclobacillus (Komitopoulou et al., 1999), Bacillus (Jaquette and Beuchat, 1998), Brochothrix (Cutter and Siragusa, 1996), Clostridium (Okereke and Montville, 1992), Enterococcus (Laukova, 1995), Lactobacillus (Chun and Hancock, 2000) Listeria (Knight et al., 1999), Micrococcus (Dutreux et al., 2000), and Staphylococcus (Thomas and Wimpenny, 1996). Gram-positive strains that are resistant to nisin have the ability to synthesize the enzyme nisinase which degrades nisin (Abee et al., 1995). Nisin is unable to penetrate the cell wall of yeast. Gram-negative bacteria are resistant to nisin; the antimicrobial is unable to
penetrate the complex cell wall, particularly the outer lipopolysaccharide membrane, to reach the cytoplasmic membrane (Kordel et al., 1989; Boziaris and Adams, 1999).

Combinations of nisin and other antimicrobial have been reported to have substantial inhibitory or killing effects against bacteria. Nisin has been successfully combined with other bacteriocins such as pediocin (Cabo et al., 2009) and leucocin F10 (Parente et al., 1998), the plant essential oils carvacrol (Pol and Smid, 1999) and thymol (Solomakos et al., 2008), lysozyme (Chun and Hancock, 2000; Mangalassary et al., 2007), EDTA (Branen and Davidson 2004; Ukuku et al., 2009), heat (Beard et al., 1999), pulsed electric fields (Dutreux et al., 2000), and high pressure treatment (Yuste et al., 1998). Nisin alone is not effective against gram negative bacteria. When nisin is combined with hurdle technology (Figure 5) its antimicrobial efficiency is enhanced by either synergistic or additive effects against both gram negative and gram positive microorganisms. Hurdle technology also offers the opportunity to provide an additional barrier and avoid the development of resistant strains.

**Figure. 5. Application of bacteriocins as part of hurdle technology.** Source: Galvez et al., 2007.
**Mechanism of action**

Numerous studies have addressed the mechanism of action of nisin (Ramsier, 1960; Gao et al., 1991; Bruno and Montville, 1993; Mol et al., 1996, 1997; Hasper et al., 2006). In susceptible vegetative cells the primary site of action by both A and Z forms is the cytoplasmic membrane (Abee et al., 1995; Kuwano et al., 2005). Nisin has the ability to bind the membrane and form pores that destroy the membrane integrity. Pore formation leads to leakage of K+ ions and ATP, depletion of the proton motive force, and depolarization of transmembrane potential, resulting in cell death (Sahl, 1991; Bruno and Montville, 1993; Millette et al., 2004). It has also been reported that nisin interferes with cell wall biosynthesis by binding with lipid II, a peptidoglycan precursor (Mantovani and Russell, 2001; Bauer and Dicks, 2005; Kruijff and Breukink). Cells with low levels of lipid II have been found to be less sensitive to nisin (Brotzel et al., 1998).

**Foodborne human enteric pathogens**

More than 250 known diseases are transmitted through food and foodborne diseases are a widespread and growing public health problem, both in developed and developing countries. The Center for Disease Control reports that foodborne diseases previously caused approximately 76 million illnesses, 325,000 hospitalizations, and 5,000 deaths in the United States each year (Mead et al., 1999). Known pathogens account for an estimated 14 million illnesses, 60,000 hospitalizations and 1,800 deaths (Mead et al., 1999). Recent data reports that foodborne disease related illnesses has declined annually causing approximately 9.4 million episodes, 55,961 hospitalizations, and 1,351 deaths (Scallan et al., 2011). Bacteria are a common cause of foodborne illness. In the past, typical examples of food transmission
vehicles were raw meats, chicken, eggs, juices, milk, and ready-to-eat meat etc. More recently other types of food products including vegetables, peanut butter, and spices have been incriminated in disease outbreaks (Natvig et al., 2002). The following human enteric pathogens among those that are of great concern to federal health agencies, food processors and consumers are *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella enterica* and *Staphylococcus aureus* (Kotula et al., 2000).

**Escherichia coli**

**Morphology and characteristics**

*Escherichia coli* is a part of the *Enterobacteriaceae* family. It is morphologically classified as a Gram-negative, non spore-forming, motile or nonmotile straight rod (1-4μm). It is a mesophilic, facultative anaerobe that is a normal inhabitant of intestines of humans and other warm-blooded animals (mammals and birds). *E. coli* is an indicator organism and its presence in food or water is generally indicative of fecal contamination. There are several pathogenic strains of *E. coli* that can be placed into 6 groups: 1) enterotoxigenic (ETEC), 2) enteroinvasive (EIEC), 3) enteroaggregative (EAEC), enteropathogenic (EPEC), diffusely adherent (DAEC), and enterohemorrhagic (EHEC) (Buchanan and Doyle, 1997; Ray, 2004). The *Escherichia coli* O157:H7 used in experiments described in the present dissertation belong to the EHEC group which is known to cause hemorrhagic colitis in infected persons. Apart from *E. coli* O157:H7 there are other major non-O157:H7 EHEC serotypes including O157:NM, O111:H8, and O26:H11 (Meng et al., 2001); however, the information in the following paragraphs will mainly focus on *E. coli* O157:H7 because it is the most common
serotype in the EHEC group and there are far more published reports on this serotype than other EHEC serotypes.

*Escherichia coli* O157:H7

In 1982 *Escherichia coli* O157:H7 was first associated with two outbreaks of hemorrhagic colitis (Wells et al., 1983). Although other *E. coli* serotypes such as O111, O26, and O126:NM (a sorbitol fermenting serotype) have been since linked to cases of hemorrhagic colitis, *E. coli* O157:H7 is the major cause of EHEC-associated illness in the United States and several countries (Meng et al., 2001). Just like all other EHEC serotypes, this pathogen produces Shiga-like toxin (Stx) or verotoxin (VT) (Johnson et al., 1983; Karmali et al., 1985). *Escherichia coli* strains that produce Shiga toxin are called Shiga toxin-producing *E. coli* (STEC) because of the strong similarity between the toxin they produce and the toxin produced by *Shigella dysenteriae* type 1 (Calderwood et al., 1996). Over 200 non O157:H7 serotypes of STEC were isolated from humans; however, only those isolates that cause hemorrhagic colitis are classified as EHEC. Other characteristics of *E. coli* O157:H7 include inability to ferment sorbitol within 24 hours, optimum growth within 30 to 42°C and pH 6 to 8, and acid tolerance although optimal pH for growth is between 6 and 8 (Tsai and Ingham, 1997). In addition, this pathogen is unable to grow well, if it does, at temperatures > 44.5°C in *E. coli* broth. It does not produce β-glucuronidase (GUD), therefore it is unable to hydrolyze 4-methylumbelliferyl-D-glucoronide (MUG), a fluorogenic substrate that is hydrolyzed by *E. coli* to produce the fluorescent 4-methylumbelliferyl moiety that fluoresces under long wave ultra violet light. This reaction helps in differentiation of *E. coli* from other organisms although a few salmonellae, shigellae
and some corynebacteria are GUD positive. *Escherichia coli* O157:H7 has an attaching and effacing (eae) gene and possesses a 60-MDa plasmid (Griffin, 1995). This pathogen can easily be destroyed by pasteurization or cooking (Williams and Ingham, 1997) therefore, undercooking and/or post-cook contamination of certain foods such as ground beef are factors that drastically increase the risk of foodborne infection by this pathogen.

**Reservoirs**

Cattle are a major reservoir for *E. coli* O157:H7. Orskov et al. (1987) reported the first isolation of *E. coli* O157:H7 from a calf (less than three weeks old) with coccobacillosis in Argentina. Generally, the prevalence of *E. coli* O157:H7 in cattle is about 10 to 25%. Interestingly, the isolation rates are much lower for non- O157 STEC. Based on results of two major surveys conducted in the United States, 31 (3.2%) of 965 dairy calves and 191 (1.6%) of 11,881 cattle on feedlots tested positive for *E. coli* O157:H7 (Zhao et al., 1995). Adult cattle seem to carry less *E. coli* O157:H7 than young cattle. In the feces of calves, populations of this pathogen range from detectable via enrichment culture (< $10^2$ CFU/g) to $10^5$ colony forming units (CFU)/g.

During the warmer months of the year there is a higher prevalence of the pathogen in cattle that correlates with the seasonal variation in *E. coli* O157:H7 infections in humans. In England, 38% of cattle delivered for slaughter in the spring tested positive for *E. coli* O157:H7 whereas, only 4.8% of cattle were positive for this pathogen during the winter season. Similarly a study in the United States revealed a high prevalence of the pathogen in cattle delivered for slaughter during July to August 1999 (Elder et al., 2000). *Escherichia coli* O157:H7 is not a pathogen of calves or adult cattle; therefore, cattle that harbor this
pathogen are not ill. Although, in some instances *E. coli* O157:H7 was linked to diarrhea and attaching and effacing lesions in new born calves (Cray et al., 1995; Dean-Nystrom et al., 1997).

Apart from cattle several domestic animals and wildlife including dogs, cats, horses, sheep, goats, pigs and deer, have been found to harbor *E. coli* O157:H7 and other STEC. These microorganisms were also found in rats and seagulls (Cizek et al., 1999; Wallace et al., 1997). Compared to other animals, sheep seem to have the highest prevalence of *E. coli* O157:H7 and STEC. Results of a survey of seven animal species in Germany revealed that STEC were most frequently isolated from sheep (66.6%), goats (56.1%), and cattle (21.1%). A much lower frequency of isolation of the pathogen was reported for cats (13.8%); pigs (7.5%), dogs (4.8%) and chickens (0.1%) (Beutin et al., 1993).

Humans can carry and shed *E. coli* O157:H7 for a substantial amount of time. In patients with hemorrhagic colitis or hemolytic uremic syndrome (HUS) the fecal shedding of this pathogen typically lasts for approximately 13 to 21 days after the onset of symptoms. Karch et al. (1995) reported that a child who was infected during an *E. coli* O157:H7 outbreak at a day care center continued to shed the pathogen for 62 days after the onset of diarrhea. To date no asymptomatic long term carriage of the pathogen in humans has been reported. Fecal carriage of the *E. coli* O157:H7 in humans is important because of the potential for person-to-person spread of this pathogen which has a low infectious dose (< 100 cells).

**Foodborne Outbreaks**

In the late 1800s *E. coli* was considered to be relatively harmless. An outbreak that caused
infants to have diarrhea in the mid 1940s resulted in some strains of *E. coli* being designated as enteropathogenic. This organism has been implicated as the contaminant in a variety of foods related to food recalls and foodborne illness. In 1982, *E. coli* O157:H7 was first recognized as a foodborne pathogen after an outbreak of hemorrhagic colitis associated with the consumption of hamburgers (Riley, et al., 1983). In 1993 consumption of contaminated hamburgers from restaurant chains caused 700 illnesses and 4 deaths across 4 states, the largest documented *E. coli* outbreak in the United States (Wachsmuth et al., 1997). United States Department of Agriculture division of Food Safety and Inspection Service identified *E. coli* O157:H7 as an adulterant in ground beef and instituted a sampling program to test for the pathogen in federally inspected establishments and retail stores in October 1994 (Griffin et al., 1994). The following food vehicles have been linked to *E. coli* O157 contamination: ground beef (Firstenberg-Eden and Sullivan, 1997), venison, sausage, dried uncooked salami, unpasteurized milk and cheese, unpasteurized apple juice and cider (Cody et al., 1999), orange juice, vegetables (alfalfa, parsley, radish sprouts, lettuce, cabbage, and spinach) (Breuer et al., 2001), fruits and berries, nuts and cookie dough. Until recently any outbreak of *E. coli* O157:H7 was assumed to be linked to raw or undercooked meat, specifically beef.

**Characteristics of the disease**

*Escherichia coli* O157:H7 infection occurs after ingestion of food contaminated with the pathogen and can result in diarrhea (non-bloody), hemorrhagic colitis (HC), hemolytic uremic syndrome (HUS), and thrombocytopenic purpura (TTP). The infectious dose (< 50 cells) to cause severe clinical syndromes is very low compared to that of several other foodborne pathogens (Bell, 2002; Ray, 2005). The incubation period is usually 3 to 4 days
with a range of 2 to 12 days. During this time the pathogen colonizes the large intestine and binds tightly to cells in the intestinal lining. During the first two days of illness infected persons experience non-bloody diarrhea and abdominal cramps that progresses to bloody diarrhea that may last for four to ten days (Besser et al., 1999). Usually, symptoms regress and stop after about one week; however, approximately 6% of infected individuals develop HUS with half of them requiring dialysis and 75% requiring blood transfusion (Cohen, 1996; Ref 32, Frontiers). Some patients endure kidney damage and occasionally kidney failure, seizures, coma and may die (Martin et al., 1990; Bell et al., 1994; Boyce et al., 1995; MacDonald et al., 1998). The fatality rate due to human infection with this pathogen is about 1% (Besser et al., 1999)

**Listeria monocytogenes**

**Morphology and characteristics**

*Listeria monocytogenes* is Gram-positive, non-spore-forming, short, roundended rod-shaped (0.5 x 1 µm) bacterium which is motile (at 28 °C) by means of peritrichous flagella. This organism is a psychrotrophic, facultative anaerobe, occurring singly or in short chains and belongs to the *Listeriaceae* family. The genus *Listeria* is separated into the following six species based on DNA relatedness: 1) *Listeria monocytogenes* – human pathogen, 2) *Listeria ivanovii* – pathogen in sheep, 3) *Listeria innocua* – non pathogenic, 4) *Listeria welshimeri*, 5) *Listeria seeligeri*, and 6) *Listeria grayi*. *Listeria monocytogenes* has several serotypes: 1/2a, 1/2b, 1/2c, 3a, 3b, 3c, and 4a, 4ab, 4b, 4c, 4d, 4e, and 7. While all serotypes are capable of causing disease in humans, serotypes 1/2a, 1/2b and 4b are responsible for about 95 to 98% of documented human listeriosis cases (Lund et al., 2000).
Listeria monocytogenes has the ability to adapt and survive exposure to many environmental stresses. This pathogen can survive and grow in a wide temperature range - 1.5 to 45°C (Juntilla et al., 1988; Vasseur et al., 1999); with optimal growth at 35 to 37 °C. Refrigeration temperature leads to delayed growth (Rosenow and Marth, 1986). This pathogen can also tolerate reduced water activity (< 0.93) by freezing or drying (Farber et al., 1992; Mena et al., 2004), high salt concentrations (up to 30%), acidic pH (below 5.0) (Bacon and Sofos, 2003), and nitrite concentrations currently approved for use in foods (ICMSF, 1996; Murray et al., 1999). These characteristics contribute to its survival under conditions usually adequate to control the growth of pathogens in food. Listeria monocytogenes is readily killed by conventional thermal processing of foods with prolonged exposure to elevated temperatures (above 56 °C) causing irreversible cellular damage resulting in death of the organism (Bunduki et al., 1995).

Reservoirs

Listeria is ubiquitous in the natural environment and therefore there are several environmental reservoirs of this pathogen. It has been isolated from soil, sewage, water, dead vegetation, human and animal feces, food processing facilities and animal feed (Beresford et al., 2001; Teixeira et al., 2008). Soils with decaying vegetation and/or fertilized with animal excreta or sewage sludge are highly likely to harbor L. monocytogenes. Interestingly, the natural habitat of this pathogen seems to be decaying vegetation such as aerobically spoiled silage, which supports prolific growth of this pathogen and serves as a source of listeriosis in farm animals (Fenlon, 1996). Due to L. monocytogenes’s widespread occurrence in nature, many feral and domestic animals carry this pathogen in their lymph
nodes and/or in their intestinal tract. About 11 to 52% of animals are carriers of this pathogen; pigs (45%) and cattle (24%) were found to carry the pathogen in their tonsils and pharyngeal lymph nodes, respectively (Doyle et al., 2007). Approximately 5 to 10% of humans exhibit intestinal carriage of this pathogen without any overt symptoms (Lorber, 1997).

*Listeria monocytogenes* can enter food processing facilities by several vehicles including raw agricultural products of plant or animal origin, clothing and shoes of workers, and possibly air-borne dust. Once this hardy pathogen enters the food processing environment it is easily spread to several areas by movement of raw materials, workers, tools, wheels of carts and actions that cause cross-contamination. *L. monocytogenes* is commonly found in moist areas such as floor drains, condensates on pipes, stagnant water, and residual food material on food processing equipment (Ryser and Marth, 2007).

**Foodborne outbreaks**

*Listeria monocytogenes* was first recognized as a human pathogen in 1929; however, it emerged as a serious food-borne pathogen in the 1980s and has been increasingly associated with food recalls and foodborne listeriosis outbreaks (Teratanavat and Hooker 2004). Five of the largest listeriosis outbreaks occurred in 1981 (Canada), 1983 (New England), 1985 (California), 1989 (multistate), and 2002 (multistate). In 1981, an outbreak related to consumption of contaminated coleslaw, resulted in 34 infected pregnant women, 9 of which experienced stillbirths, 23 had infected infants, and 2 had healthy births. There were 77 other adults who developed listeriosis with nearly 30% mortality. The outbreak in 1983 was caused by drinking a specific brand of pasteurized whole or 2% milk contaminated by *L.*
monocytogenes serotype 4b, resulted in 49 patients acquiring listeriosis; 7 fetuses or infants and 42 immunocompromised adults; of these 14 patients died (Fleming et al., 1985). In California (1985), 142 people developed listeriosis from consuming a certain brand of pasteurized soft cheese that had been cross contaminated with raw milk during the manufacturing process. Of those 93 cases were perinatal, 49 non pregnant, and 48 immunosuppressed individuals, of which 30 fetuses or newborn infants and 18 adults died (ICMSF, 1996). The 1989 multistate outbreak linked to meat frankfurters, resulted in 108 cases, with 14 associated deaths and 4 miscarriages or stillbirths (Mead et al., 2006). In 2002, a multistate outbreak of L. monocytogenes infection with 46 culture-confirmed cases, seven deaths, and three stillbirths or miscarriages in eight states was linked to eating sliced turkey deli meat. USDA established a zero tolerance policy for L. monocytogenes in ready-to-eat meat products (USDA, 1987, 1989). Many different foods have been associated with being contaminated with L. monocytogenes: minced meats, improperly cooked chicken, dairy products, fish and seafood, eggs, paté, pork, rice salad, butter, and potato salad (Schlech et al., 1983; Cox 1989; Schuchat et al., 1992; Vasseur et al. 1999; Rocourt et al., 2000; Pawar et al., 2000; Ryser and Marth, 2007). Listeria is responsible for the foodborne illness listeriosis and is of significant concern to the food industry (Cox, 1989; Wong, 1998).

**Characteristics of listeriosis**

Listeriosis, an opportunistic disease, represents a small fraction of all illnesses related to bacterial foodborne pathogens but accounts for 3.8% of hospitalizations and 27.6% of deaths (Mead et al., 1999). Foodborne infection occurs after consuming contaminated food, enabling listeria to penetrate the epithelial lining and cross the intestinal barrier. The pathogen is believed to become attached to epithelial cells of the GI tract by means of D-
galactose residues on the bacterial surface which adhere to D-galactose receptors on the host cells (Dramsi et al., 1993). The organism becomes engulfed by macrophages and encased in a vacuole. Within the macrophage the pathogen eventually lyses the vacuole and invades the cytoplasm, where it begins to multiply. A virulence factor that helps the pathogen to escape from the vacuole is listeriolysin O (LLO), and hemolysin which produces a zone of beta-hemolysis around the listerial colony on blood agar (Lorber, 1997; Salyers and Whitt, 2002). The internalized pathogen is transported to lymph nodes then to the liver, which is a primary area of infection. Within the macrophage the pathogen can spread through the bloodstream to other body tissues also while being protected from the host’s antibodies. Except for macrophages which are naturally phagocytic, other host cells such as enterocytes are invaded by the pathogen via special membrane proteins (In1A and In1B) called internalins (Gaillard et al., 1991) which facilitate adhesion to and invasion of the host cell (Lorber, 1997; Salyers and Whitt, 2002).

Spread of *L. monocytogenes* in the human body can cause infection at several sites leading to septicemia, meningitis, abortions and stillbirths, gastroenteritis and death. Listeriosis is regarded as a major problem especially in high risk groups including pregnant women, fetuses, neonates, the elderly and immunocompromised individuals (30 to 40% fatality) (Farber and Peterkin, 1991). *L. monocytogenes* is one of very few infectious microorganisms that are capable of traversing the placental barrier and infesting the fetus. An infected pregnant woman may experience mild flu-like symptoms; however, the fetus usually develops a systemic infection, which is highly lethal (Lorber, 1997). The tragic reality of listeriosis in pregnant women is that there is no early warning sign of the disease.
The only first symptom is an infected neonate or a stillborn infant. In immunocompromized individuals, the first sign of listeriosis infection is usually fever and the disease rapidly progresses to other complications, commonly meningitis (Lorber, 1997). Healthy individuals may not develop symptoms or show very mild symptoms. Common symptoms for healthier individuals are mainly enteric (abdominal cramps, diarrhea, nausea) along with a slight fever and headache. A major reason why listeriosis is an uncommon disease among immunocompetent persons is that the pathogen has a relatively high infectious dose (ID$_{50}$). The ID$_{50}$ is a measure of infectivity and refers to the number of viable cells of the pathogen required to cause infection in 50% of experimentally infected animals. Due to the high ID$_{50}$ of *L. monocytogenes*, healthy persons have to ingest large numbers of viable cells of the pathogen to contract a mild infection. Treatments such as antacids or H$_2$ blockers that compromise the acid protection in the stomach can increase a person’s susceptibility to listeriosis. Pregnancy also increases a person’s susceptibility to this foodborne infection (Lorber, 1997). Symptoms of listeriosis appear between 11 and 70 days (average 30 days) after ingestion of contaminated food. This protracted incubation period presents a major impediment to accurately tracing the source of an outbreak because people are unable to accurately recall food consumed 30 days ago (Broome, 1993).

**Salmonella**

**Morphology and characteristics**

*Salmonella* is a genus of the *Enterobacteriaceae* family. It is morphologically classified as a Gram-negative, non spore-forming, usually motile, medium rod (1 x 4 µm). The normal habitat, of this mesophilic, facultative anaerobe is the gastrointestinal tract of animals, birds, insects, and some reptiles (turtles and frogs). The *Salmonella* genus is
divided into two species, *Salmonella enterica* and *S. bongori*. *S. enterica* is further divided into six subspecies: (I) *S. enterica* subsp. *enterica*, (II) *S. enterica* subsp. *salame*, (IIIa) *S. enterica* subsp. arizonae, (IIIb) *S. enterica* subsp. diarizonae, (IV) *S. enterica* subsp. *indica*, and (IV) *S. enterica* subsp. *houtenae* (Porwollik et al., 2004; Ray 2004). Within subspecies I there are over 2500 serovars and all are considered human enteric pathogens.

The growth range for *Salmonella* is from 5-46°C and optimum growth temperature is between 35 and 37°C. *Salmonella* are generally sensitive to heat (pasteurization temperature and time) and high acidity (pH 4.5 or below), depending on food product and processing. Heat resistance can be developed in dry products (powdered milk) or low water activity products (peanut butter - aW < 0.35) (Burnett et al., 2000; Shacher and Yaron, 2006). As the water activity decreases in a food product the pathogen becomes more heat resistant. As with other pathogens food composition (fat and protein content) must be considered when determining possible heat resistance of *Salmonella*. The cells also have the ability to survive (not multiplying) in suboptimal (frozen, dried, or nutrient starved) states for long periods (Foster and Spector 1995).

**Reservoirs**

The widespread occurrence of *Salmonella* in the natural environment is most likely attributed to several reservoirs of this pathogen. The continued prevalence of *Salmonella* in the global food chain is due to the pathogen’s widespread occurrence along with intensive production practices employed by poultry, cattle, swine, fish and shellfish industries and the recycling of animal visceral organs and inedible raw materials into animal feeds (D’Aoust, 2000). For several decades, poultry and poultry products have been well known as important
reservoirs for salmonellae and have obscured the importance of meats including beef, pork, and mutton as potential sources of Salmonella infection in humans (Hedberg et al., 1999; Todd, 1994; World health Organization, 1988). In its attempt to address this problem, the USDA Food Safety and Inspection Service (FSIS) published the “Final Rule on Pathogen Reduction and Hazard Analysis and Critical Control Point (HACCP) Systems” in July 1996. According to the Final Rule the meat and poultry processors are required to implement HACCP plans and systematically sample final products for fecal indicator (Escherichia coli biotype 1). Also, FSIS performs testing of the finished meat products for Salmonella to ascertain that the HACCP system is adequate to control of this pathogen. Before implementation of the Final Rule, the Salmonella contamination rate in processed broiler chickens was 24%. By 1999 the contamination rate decreased to approximately 11%. In a more recent survey of 20 U.S. broiler processing plants, the contamination rate was 20% for post-chill carcasses (Berrang et al., 2009). Based on these findings, future improvement in reducing prevalence of Salmonella in meat and poultry products will require stringent control measures on animal production farms, and during processing, distribution and handling at retail sites.

Apart from poultry and other meats, eggs have been frequently identified as a reservoir of Salmonella and a vehicle for the spread of the pathogen in humans. The pandemic linked to Salmonella enterica serotype Enteritidis phage type 4 and phage type 8 in Europe and North America, respectively, has been associated with the consumption of eggs (raw or lightly-cooked) and egg-containing products. This pandemic further justifies the need for continued stringent pathogen control measures in poultry and egg production. More focus should also be placed on pathogen control in breeder flocks because it is known that S.
Enteritidis can infect the ovaries of laying hens and enter the egg before the shell is produced. This process is termed transovarian transmission in which the infective agent contaminates the egg prior to deposition of the shell. Obviously, no amount of surface sanitizing of whole eggs can destroy the pathogen which is inside of the egg and remains viable.

Intensive fish farming involving improper management practices have created a relatively new reservoir of *Salmonella*. Within the past three decades there has been an increase in aquaculture of various fish and shellfish species globally as alternative sources of these food products. This trend resulted from the noticeable depletion of feral stocks of fish and shellfish and led to intensive (high-density) inland farming of these fish to satisfy the growing consumer demand. This type of intensive aquaculture has contributed to the widespread contamination of fish in unprotected earth, concrete, or other types of ponds that are continuously exposed to environmental contaminants. In the U.S. a substantial amount of aquaculture products are imported from south American, Asian, and African countries where aquaculture farmers may be using questionable management practices that may increase the populations of salmonellae in pond-raised fish. In some countries it is common practice to feed pond-raised fish with raw pieces of meat, offal, night soil and/or animal feeds that may be contaminated with various serovars of *S. enterica*. The feeding of pond-raised fish with night soil is a serious public health concern because that type of feed could potentially carry typhoid and paratyphoid salmonellae. Such practices perpetuate the occurrence of high populations of salmonellae and other human enteric pathogens and create a constant source of contamination in the production environment (D’Aoust, 1994). In addition, they at times increase the populations of fish pathogens which cause sub-optimum growth or death of the
fish and severe economic loss to aquaculture farmers. To safeguard the health of fish and shellfish and reduce financial losses, aquaculture farmers are relying on the sub-therapeutic use of antibiotics such as chloramphenicol, sulfa drugs, ampicillin and fluoroquinolones. This management practice is short-sighted and irresponsible because such misuse of medically important antimicrobials in animal production selects for antibiotic-resistant \textit{Salmonella} serovars (D’Aoust, 1994; D’Aoust et al., 1992). This in turn can have severe health consequences when consumers eat pond-raised fish in a sushi meal or in a lightly cooked form, or shellfish, contaminated with antibiotic-resistant salmonellae (D’Aoust, 1994; D’Aoust et al., 1992).

In recent years fresh fruits and vegetables have emerged as vehicles of human salmonellosis (Harris et al., 2003). Factors that contribute to that situation include increased imports of fresh and dehydrated vegetables from foreign countries that have a tropical climate year round. Also, in those countries, hygienic conditions during crop production, harvesting, and distribution may not meet minimum U.S. standards thus facilitating microbial contamination of fresh produce. More importantly, the fertilization of crops with untreated sewage or non-composted animal manure, irrigation of fields and washing of fresh produce with contaminated water, improper handling of produce by workers, and numerous other opportunities for environmental contamination of dried vegetables and spices during the drying process are factors that facilitate the accumulation of human enteric pathogens including \textit{Salmonella} for which several reservoirs exist.

\textbf{Foodborne outbreaks}

The current increase in salmonellosis in the U.S. may be related to four factors: (1)
increased number of antimicrobial-resistant *Salmonella* isolates, (2) increased immunodeficient individuals, (3) increased egg-associated *Salmonella* Enteritidis contamination due to increased laying hens with infected ovaries, and (4) centralized food production that increase the risk of widespread distribution of contaminated food to cause large outbreaks (Tauxe, 1984). *Salmonella enterica* serotype Typhimurium and *Salmonella enterica* serotype Enteritidis have been the most frequently reported causes of foodborne illnesses since 1993. The Center for Disease Control and Prevention (CDC) 2011 Estimates of Foodborne Illness report linked to *Salmonella* are 1,027,561 illnesses, 19,336 hospitalizations, and 378 deaths. The twenty most common serotypes of *Salmonella* in 2006 represented 70% of all *Salmonella* isolates. The four most common serotypes were Typhimurium, Enteritidis, Newport, and Heidelberg (45% of all isolates; CDC, 2008). There were 121 outbreaks in 2006, and more than 3,300 illnesses (Enteriditis (26), Typhimurium (26), Newport (10), and Heidelberg (10); CDC, 2006). Raw or undercooked chicken and eggs are usually the foods thought to be most commonly associated with *Salmonella*; however, from 2006 to 2011, various serovars of *Salmonella* have been linked to contamination of the other foods including: tomatoes, banquet pot pies, dry pet food, peanut butter, cantaloupes, Malt-O-Meal Rice/wheat cereals, pistachios, alfalfa sprouts, red and black pepper, gourmet seasoning, soup/dip mixes, vegetable broth, granola bars, ceviche, potato chips, and eggs (http://www.cdc.gov/salmonella/outbreaks.html). During 2004, a multistate outbreak of serotype Javiana infections associated with tomatoes at a gas station deli chain affected more than 400 people in 5 states (CDC, 2008). *Salmonella* Tennessee was involved in a notable outbreak associated with peanut butter distributed worldwide, and caused over 700 cases of illness in 48 states (CDC, 2007a). In 2006, two *Salmonella*
(Newport and Typhimurium) outbreaks were associated with consumption of raw tomatoes in restaurants causing a total of 309 illnesses (CDC, 2007b). In 2009 there was a multistate outbreak of Salmonella Typhimurium associated with peanut butter and peanut butter containing products resulting in 529 people infected in 43 states, 116 people hospitalized and 8 deaths. In August 2010, there were two recalls related to eggs contaminated with Salmonella Enteritidis from two farms located in Iowa. Approximately 550 million eggs were recalled nationwide; more than 2000 people were sickened, between May 1, 2010 and Nov 30, 2010 (CDC, 2010). Based on these previously mentioned outbreaks, salmonellosis continues to be a major food safety problem in the United States. Therefore, much greater attention needs to be paid to control the pathogen at all points in the food chain from farm to consumer.

**Characteristics of salmonellosis**

Salmonellosis in humans can cause serious ailments including enteric (typhoid) fever, enterocolitis, and systemic infections. Typhoid and paratyphoid serovars of the pathogen are able to invade and survive in human intestinal cells and subsequently cause enteric fever, a serious human disease. Symptoms of enteric fever occur after an incubation period of 7 to 28 days and may include nausea, diarrhea, fever, abdominal pain, headache, and prostration (D’Aoust, 1991). Disease diagnosis depends on isolation of the pathogen from the patient’s blood and urine in the initial stages of infection or from fecal material after the onset of symptoms (D’Aoust, 1989). Following the acute phase involving enteric fever, the patient usually enters an asymptomatic chronic carrier state. Antibiotics such as chloramphenicol, ampicillin, or trimethoprim-sulfamethoxazole are used to treat patients with enteric fever to
eliminate the systemic infection. Within the past two decades marked global increases in antibiotic-resistant *Salmonella* have challenged the efficacy of antibiotic therapies. This problem is further exacerbated in developing countries where outbreaks of enteric fever are frequently associated with salmonellae that exhibit multiple antibiotic resistance and cause unusually high mortality rates (Carmen Palomino et al., 1986; Rajajee et al., 1995).

Salmonellosis caused by non-typhoid *Salmonella* serovars usually results in enterocolitis and abdominal pain although systemic infections may occur in some instances. The pathogen invades the mucosa of the small intestine, proliferates in the epithelial cells, produces a toxin and causes inflammation. After invasion of the epithelial cells it multiplies and produces an enterotoxin. Symptoms may appear in 6 to 48 hours after ingestion of contaminated food or water. Acute symptoms include nausea, vomiting, abdominal cramps, non-bloody diarrhea, chills, fever, headache and prostration lasting 2 to 3 days or more. Generally, the disease is self-limiting and regression of diarrhea and abdominal pain occurs within 5 days after the onset of symptoms (D’Aoust, 1989). Although it was previously thought that relatively large amounts of the pathogen had to be ingested to cause disease, the infectious dose of *Salmonella* can be relatively small (15-20 cells) depending on the serotype. Chronic symptoms include enlargement of the liver and spleen, infection of tissues surrounding the brain and spinal cord, and reactive arthritis (Mayo Clinic, 2009, April 17). Salmonellosis can be fatal to elderly, infants and immune compromised individuals.

*Staphylococcus aureus*

**Morphology and characteristics**

The etymological root of the bacterium’s name: *staphylo* (bunch of grapes) is derived
from Greek and *aureus* (golden) is derived from Latin. The organism’s name pertains to the gold colonies that are formed on agar medium. *Staphylococcus aureus* is gram-positive, non-spore forming, non motile, spherical cells (0.5 to 1 µm) occurring singly, in pairs, or in grape-like clusters. The main habitat of this mesophilic, facultative anaerobe is on human skin, mouth or nose, and animal hides, feathers, and skin. The genus *Staphylococcus* belongs to the bacterial family *Staphylococcaceae*. More than 20 species of *Staphylococcus*, some pathogenic and some non-pathogenic, have been delineated by DNA hybridization (Kloos and Schleifer, 1986; Freney et al., 1988). Several *Staphylococcus* species have been implicated in human infections, notably *S. aureus*, *S. saprophyticus*, *S. epidermidis*, *S. lugdunensis*, and *S. schleiferi* (Tenover and Gayne 2000; von Eiff et al., 2002; Choi et al., 2006; Otto, 2009). Many strains are known to be enterotoxin producers; however, their involvement as foodborne pathogens is unknown (Becker et al., 2001). *S. aureus* is the most common strain associated with human foodborne illness.

*Staphylococcus aureus* strains can be classified into the following 6 biotypes according to their human or animal origin: a) human, b) non-β-hemolytic human, c) avian, d) bovine, e) ovine, and f) nonspecific (Devriese, 1984). Generally, *S. aureus* strains produce at least 34 different extracellular enzymes, toxins, and other chemical components; however, strain differences occur and no one strain is capable of producing all of these proteins (Landolo, 1989). Nearly all strains of *S. aureus* produce the enzymes coagulase, thermonuclease, and hemolysin and are also resistant to digestive proteolytic enzymes, such as trypsin and pepsin (Le Loir et al., 2003). There are two groups of heat stable enterotoxins produced by *S. aureus*, Group 1: A, B, C1, C2, C3, D, and E; Group 2: G, H, I, J, K, L, M, N,
O, P, Q, R, and U (Dinges et al., 2000; Jarraud et al., 2001; Baba et al., 2002; Omoe et al., 2002).

Several factors influence enterotoxin production in foods and the extent to which the toxin may cause foodborne illness. Factors include numbers of viable *S. aureus* in the food, type and composition of food, holding temperature, amount of food consumed, presence of inhibitors, health of the consumer, susceptibility to the toxin, and type of toxin produced (Doyle et al., 1997). Rate of toxin production by a strain is directly related to its rate of growth and cell concentrations. Viable cells of *S. aureus* at a level greater than $10^5$ or $10^6$ per gram of food have been associated with enterotoxin production at concentrations sufficient to cause disease even though lower viable numbers of the pathogen have at times been implicated in causing foodborne disease. Enterotoxin concentrations ranging from 1-5 µg have been demonstrated in foods involved in many *S. aureus* food poisoning outbreaks; however, enterotoxin doses as little as 10 nanograms or less can cause food poisoning (Doyle et al., 1997).

Growth temperature of *S. aureus* ranges from 7 to 47.8 °C and optimal growth temperature range is 30 – 35 °C (Schmitt et al., 1990). Cells can be killed by heating at 66 °C for 12 minutes and at 72 °C for 15 seconds. The pH range for growth of the pathogen is 4.5 to 9.3 (Scott, 1953) whereas, the optimum pH for growth is between 7.0 and 7.5 (Bergdoll, 1989; Martin and Myers, 1994). *S. aureus* is highly tolerant to salt (up to 10%) and sugars and can grow within a water activity ($a_w$) range 0.83-0.99. Although the pathogen may grow at $a_w$ as low as 0.83, a minimum $a_w$ of 0.86 is required for enterotoxin production (Lund, 2000). The ability of *S. aureus* to grow at 6–7 °C, low pH, and low water activity levels depends on other intrinsic or extrinsic factors being optimal for the pathogen.
Ability to grow under several adverse conditions allows the pathogen to multiply without intense competition from normal microflora present in food. Eradication of staphylococci is not always successful due to their ability to form biofilms (Nostro 2007). *Staphylococcus aureus* strains are frequently involved in foodborne intoxications.

**Reservoirs**

Humans and animals are important reservoirs of *S. aureus*. This pathogen and other staphylococci can be found on skin and skin glands of humans, other mammals and birds. It has been isolated from nostrils, mouth, upper respiratory tract, mammary glands, intestinal tract and genitourinary tract of infested hosts (Murray et al., 1999). The anterior part of the nasal passages is a well-known site for colonization of *S. aureus*, although the pathogen can be found on the skin. It is estimated that about 50% of healthy humans naturally carry *S. aureus* as part of their normal microflora (Jay et al., 2005). Contamination of food with this pathogen can occur by direct contact of food with contaminated hands of workers. Also, food contamination may occur indirectly from shed skin cells or aerosols generated from coughing and or sneezing, which expel droplets from the respiratory tract. The majority of sources of staphylococcal food poisoning have been traced to humans who contaminated foods during preparation or improper handling following preparation. Generally, animals may harbor very high populations of *S. aureus* (Jay et al., 2005). Colonization of animals with this human enteric pathogen is of major public health concern because of the potential for contamination of foods of animal origin before or during processing. Other sources for transfer of the pathogen to food include equipment and materials used in food processing such as improperly cleaned and sanitized meat grinders, saws blades, knives, cutting boards,
and food storage containers. Apart from being on the human body or on food processing implements, *S. aureus* can persist for extended periods of time in a desiccated state. This pathogen is one of the most resistant non-spor-forming pathogens and has been isolated from air, dust, water and sewage (Doyle et al., 1997).

**Foodborne outbreaks**

The growth and proliferation of *S. aureus* in foods presents a potential hazard to consumer health since many strains of *S. aureus* produce enterotoxins. The association of staphylococci with foodborne illness dates back as early as 1884, when a large food poisoning outbreak in the U.S. was linked to contaminated cheese. In 1989 the consumption of canned mushrooms contaminated with *S. aureus* enterotoxin A, caused multiple staphylococcal foodborne outbreaks (Feb. 13, Feb. 28, and April 17; Hard-English et al., 1990). These outbreaks led to 82 sick individuals, and of those 12 were hospitalized. Between 1993 and 1997, 42 outbreaks occurred, involving 1,413 cases, and one death (CDC, 2002). Based on the Center for Disease Control and Prevention (CDC) 2011 Estimates of Foodborne Illness for 2011, approximately 241,148 illnesses will be associated with *S. aureus*. Foods commonly associated with staphylococcal food poisoning include meat and meat products, fish, eggs, fruits and vegetables (mashed potatoes), salads, cream-filled bakery products, dry pasta and dairy products (Bean and Griffin, 1987; Evenson et al., 1988; Bean et al., 1990; Ray, 2005). Many of these items are contaminated post processing, during food preparation in homes, food service establishments, or mishandling prior to consumption (temperature abuse, poor hygiene). Human intoxication is caused by ingesting enterotoxins
produced in food, usually because of temperature abused food (hot holding temperature below 60°C or cold holding temperature above 4 °C).

**Characteristics of *Staphylococcus aureus* intoxication**

Staphylococcal food poisoning (staphylococcal gastroenteritis) is a self-limiting illness due to the absorption of staphylococcal enterotoxins preformed in the food (Le Loir et al., 2003). Generally, a toxin level that results in human illness is reached when *S. aureus* populations exceed $10^6$ colony forming units. The infectious dose varies and a healthy adult must consume 30 g or ml of food containing 100 to 200 ng toxins to experience illness whereas, lower amounts of the toxin have caused illness in immune-compromised individuals (Bergdoll, 1990; Ray, 2005). Severity of symptoms is directly related to an individual’s susceptibility, general health, potency and amount of toxin ingested. The onset of symptoms can occur anywhere from 30 min to 8 hours (2 - 6 hours average) after consumption of contaminated food containing preformed toxin (Dack, 1956). Primary symptoms are abdominal cramps, nausea, vomiting, occasionally followed by diarrhea (never diarrhea alone) and prostration. Secondary symptoms include dehydration, headache, chills, fever, transient changes in blood pressure and pulse rate. Recovery typically takes 2 days. More serious symptoms include toxic shock syndrome (release of super antigens into the blood stream), pneumonia, mastitis, phlebitis, meningitis, urinary tract infections, osteomyelitis and endocarditis. Death related to staphylococcal food poisoning is very rare. For the general public the fatality rate is about 0.03%; however, this rate increases to about 4.4% for more susceptible groups such as young children and the elderly (Holmberg and Blake, 1984).
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CHAPTER 3

INFLUENCE OF PHOSVITIN, CARVACROL AND THEIR COMBINATION ON THE VIABILITY OF SALMONELLA ENTERICA AND LISTERIA MONOCYTOGENES IN ONION MUSHROOM SOUP HELD AT 12 °C OR 35 °C

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Key words: Listeria, Salmonella, phosvitin, carvacrol, soup
Abstract

The antibacterial effect of phosvitin or carvacrol alone or combined, against *Salmonella enterica* and *Listeria monocytogenes* in brain heart infusion (BHI) broth and onion mushroom soup was investigated. Broth with added phosvitin (10, 20, 40, 60, 80 or 100 mg/ml), or carvacrol (0.09, 0.12, 0.14, 0.19, 0.38, or 0.75 mg/ml) was inoculated with *S. enterica* or *L. monocytogenes* to a final concentration of 5.0 log CFU/ml per pathogen. Broth or soup without antimicrobials served as control. Growth of *S. enterica* and *L. monocytogenes* in BHI (35 °C, 24 hours) was monitored using a Bioscreen C turbidometer (OD 600nm). Growth of the pathogens in soup (12 °C, 8 days) and (35 °C, 24 hours) was monitored by surface plating samples. In BHI broth the minimum inhibitory concentration (MIC) of phosvitin and carvacrol was 80 mg/ml and 0.14 mg/ml, respectively, for both *S. enterica* and *L. monocytogenes*. In soup (12 °C) all antimicrobial treatments tested decreased viable counts of both pathogens after 2 days of storage. In control soup viable numbers increased to 6.95 and 8.72 log CFU/ml at day 8 for *S. enterica* and *L. monocytogenes*, respectively. In soup (35 °C) viable counts of the pathogens were decreased by the higher concentration of carvacrol (0.40 mg/ml) and phosvitin (60 mg/ml) plus carvacrol concentrations (0.20 or 0.40 mg/ml). The combination of phosvitin (60 mg/ml) and carvacrol (0.40 mg/ml) exerted the greatest cidal effect throughout storage against *S. enterica* and *L. monocytogenes*.

Introduction

The growing number of foodborne illness-related outbreaks due to human enteric pathogens
is an increasing concern to regulatory agencies, the food industry, and consumers. While effective control of foodborne pathogens is crucial to ensuring microbial food safety, methods of control involving synthetic chemical preservatives are becoming less desirable to consumers. This consumer attitude is part of a growing trend towards “Green Consumerism” emphasizing the reduction or elimination of preservative agents such as nitrite and sodium chloride from foods (5) and encouraging the use of natural antimicrobials from animal, plant or microbial sources to preserve foods, promote healthier foods and improve food safety.

Phosvitin is a 35 kDa glycoprotein found exclusively in the granule fraction of chicken egg yolk, making up 7% of the yolk protein and 80% of the protein bound phosphorus (39, 49). This 217 amino acid peptide is composed of over 50% serine residues, of which 90% are phosphorylated (6, 7, 41). Phosvitin contains between 3 to 6 iron atoms per molecule depending on the method of isolation from hens’ eggs; however, it has a binding capacity of about 60 iron molecules (2, 26, 40, 51). Phosvitin is a strong metal chelator and could be used as an antimicrobial agent. To date there is only one published report demonstrating the antibacterial activity of phosvitin (37). Researchers found that the combination of phosvitin and thermal stress (50 °C) was bactericidal against Escherichia coli. It is likely that phosvitin sensitized this organism to the lethal effects of heat in a laboratory broth medium.

Herbs and spices have been used for centuries specifically for medicinal purposes, flavor, fragrances, and as natural preservative methods for a variety of foods (1, 8). The majority of essential oils are classified as Generally Recognized As Safe (GRAS). The phenolic compounds in the essential oil fraction of the plant possess antimicrobial properties
(4). Carvacrol is an essential oil found in the leaves and flowering plant of both thyme (*Thymus vulgaris*) and oregano (*Origanum vulgare*) (5, 31). The percent composition of carvacrol in oregano ranges from trace amounts to 82% and 2 to 45% in thyme (3, 5, 23). The hydrophobic phenolic compound in its structure is though thought to be the main contributor to its antimicrobial properties (47). Several studies have demonstrated that carvacrol has both bacteriostatic and bactericidal activity against microorganisms including: *Listeria monocytogenes* (10, 12, 17, 31, 33, 34, 35, 38, 48), *Bacillus cereus* (35, 42-47), *Escherichia coli O157:H7* (10-12, 14, 16, 29, 31-33, 52), *Staphylococcus aureus* (20, 24, 31), and *Salmonella enterica* (11, 14, 20, 22, 28, 36, 53). Carvacrol has been shown to possess stronger antimicrobial effect with increased temperature and storage time, and at a lower pH (5, 11).

The antimicrobial properties of both of these natural antimicrobials may be used to improve microbial safety of foods, with combined use possibly increasing the effectiveness of the antimicrobial treatments against foodborne pathogens. Also, synergy between two of these antimicrobials may permit the use of relatively lower amounts of each antimicrobial and thereby reducing cost of the antimicrobial treatment. While there is a growing body of knowledge on the antimicrobial effects of carvacrol against various foodborne pathogens, such published research involving phosvitin is scarce. To our knowledge there is no published research involving the combined use of phosvitin and carvacrol against *Salmonella enterica* and *Listeria monocytogenes*. Accordingly the objective of the present study was to evaluate the antimicrobial efficacy of phosvitin, carvacrol and their combinations in onion mushroom soup held at 12 °C or 35 °C.
**Materials and Methods**

**Bacterial cultures and culture conditions.** Five strains of *Listeria monocytogenes* (H7962-4b, H7762-4b, H7596-non4b, H7969-4b, and NADC-2045-4b) and five serotypes of *Salmonella enterica* (Enteritidis-ATCC13076, Heidelberg, Typhimurium-ATCC 14802, Gaminara-8324, Oranienburg-9329) were obtained from the culture collection of the Microbial Food Safety Laboratory, Iowa State University, Ames, IA. Stock cultures were kept frozen (−70 °C) in Brain Heart Infusion (BHI) broth (Difco, Becton, Dickinson, Sparks, MD) supplemented with 10% (vol/vol) glycerol. Stock cultures were activated in BHI broth (pH 7.2) and incubated at 35 °C. At least two consecutive 18 to 22-h transfers of each stock culture were carried out before using the cells as inocula in each experiment.

**Preparation of Inoculum.** An equal volume of the individual working cultures of *L. monocytogenes* or *S. enterica* were combined in a sterile centrifuge tube. The cells were harvested by centrifugation (10,000 x g, 10 min, 4 °C) using a Sorvall Super T21 (American Laboratory Trading, Inc., East Lyme, CT) and washed once in 0.1% (wt/vol) peptone. The pelleted cells were suspended in fresh 0.1% (wt/vol) peptone to obtain a final viable cell concentration of approximately 10⁹ CFU ml⁻¹. Viable counts of the washed cell suspensions were evaluated by surface plating serially diluted (10-fold) samples on tryptic soy agar supplemented with 0.6% yeast extract. The individual cell suspensions were used to inoculate BHI broth or commercial onion mushroom soup.

**Antimicrobials.** Phosvitin was supplied by Dr. Dong Ahn from the Department of Animal Science at Iowa State University, Ames, IA. A commercial preparation of carvacrol
was purchased from Sigma-Aldrich (Aldrich W224502).

**Total phenolic content of carvacrol.** The concentration of total phenolics of carvacrol was determined using the method described by Waterman and Mole (50). The assay involves reduction of ferric iron to the ferrous state by phenolic compounds that results in the formation of the Prussian blue complex Fe₄[Fe(CN)₆]₃ with a potassium ferricyanide reagent. The Prussian blue complex was determined colorimetrically (18). Two separate 1% (vol/vol) solutions of carvacrol in 10% (vol/vol) ethanol and deionized water were prepared. The absorbance of three sub-samples from each solution was measured at 720 nm and the total phenolic content expressed as the number of catechin equivalents x 100.

**Preparation of treatment solutions for Bioscreen C Assay.** BHI broth with added phosvitin (10, 20, 40, 60, 80, 100 mg/ml) or carvacrol (0.09, 0.12, 0.14, 0.19, 0.38, or 0.75 mg/ml) was filter sterilized using 0.22 μm pore size Millipore filters (Fisher Scientific, Pittsburgh, PA). Samples (2.5-ml) of the treatment solutions and control (BHI with no added antimicrobial) were each inoculated with 25 μl of diluted (1:100) *L. monocytogenes* or *S. enterica* cell suspension to obtain a final concentration of approximately 10⁵ CFU/ml of sample.

**Bioscreen C assay.** Aliquots (200-μl) of inoculated samples were added in triplicate to the wells of microtiter plate for the Bioscreen C Turbidometer (Growth Curves, Piscataway, NJ), an automated microbial growth analyzer and incubator. Plates were incubated in the Bioscreen C at 35 °C for 24 h and the instrument was programmed to record optical density (OD) measurements at 600 nm every 30 min, with shaking of samples before
each OD reading. Minimum inhibitory concentration (MIC) was defined as the lowest treatment concentration that completely inhibited microbial growth for 24 hr (< 0.05 OD unit increase).

**Preparation and inoculation of soup.** Dehydrated onion mushroom soup/dip mix was purchased from a local grocery store. The soup mix was hydrated with sterile distilled water and prepared according to the directions stated on the package. Soup ingredients are shown in Table 1. After boiling, the soup was tempered to ~ 35 °C and 10-ml portions of the soup were aseptically transferred into sterile 30 ml screw cap Pyrex tubes. Phosvitin, carvacrol or combinations were added to each tube to yield the following concentrations: phosvitin (60 mg/ml), carvacrol (0.20 mg/ml or 0.40 mg/ml), phosvitin (60 mg/ml) + carvacrol (0.20 mg/ml) and phosvitin (60 mg/ml) + carvacrol (0.40 mg/ml). Phosvitin was added to the tube prior to the addition of the soup to prevent aggregation and facilitate its dissolving in the soup. Tubes of soup without added antimicrobial served as control. The treatments were then warmed or cooled to the target temperature. Tubes of soup with added antimicrobials were mixed by vortexing and inoculated with a suspension of washed cells of *S. enterica* or *L. monocytogenes* to generate a final cell concentration of approximately $10^5$ CFU/ml for each pathogen. After inoculation, each tube of soup was gently mixed by vortexing and held at either 12 °C or 35 °C.

**Microbiological analysis.** Inoculated tubes, of soup held at 12 °C, were tested for survivors of the pathogens every 2 days for a total of 8 days whereas, soup, held at 35 °C, were tested at 4, 8, 12 and 24 h. Ten-fold serial dilutions of the soup were prepared using 0.1% (wt vol/vol) peptone with added Tween 80. Aliquots (1.0 ml or 0.1ml) of the soup or
diluted samples of soup were surface plated (in duplicate) on xylose lysine desoxycolate (XLD) agar (for *S. enterica*) and modified oxford medium (for *L. monocytogenes*). All inoculated plates were incubated at 35 °C for 48h before counting bacterial colonies.

**Measurement of pH and water activity.** Measurements of pH were taken using an Orion Model 525 pH meter (Orion Research, Inc., Boston, Massachusetts) fitted with a glass electrode. Water activity measurements were made using the Aqualab CX2 water activity meter (Decagon Services, Pullman, Washington). The initial pH and water activity of each sample of soup, including controls, was measured at day 0 (prior to inoculation). Measurements of pH were also taken periodically during storage of the soup at 12 °C or 35 °C.

**Statistical analysis.** Three independent replications of each experiment were performed. Mean numbers of viable *L. monocytogenes* or *S. enterica* were statistically analyzed using SAS statistical software version 8.1 (SAS Institute Inc., Cary, N.C.). Treatment means were evaluated for statistically significant differences using Tukey’s test. Significant differences were defined at P < 0.05 for all the experimental data.

**Results**

**Inhibitory effect of phosvitin in BHI broth.** Figures 1 and 2 show the effect of various levels of phosvitin on the growth of *Salmonella enterica* and *Listeria monocytogenes*, respectively, in Brain Heart Infusion (BHI) broth at 35 °C. For *S. enterica* the optical density (OD) of control and BHI broth containing 10 mg/ml phosvitin increased rapidly and reached OD greater than 1.2 within 18 hours. Growth inhibition of *S. enterica* markedly increased
with higher phosvitin concentrations. Compared to control and 10 mg/ml, all concentrations of phosvitin extended the lag phase of the pathogen. Phosvitin concentrations of 80 and 100 mg/ml were bacteriostatic. The minimum inhibitory concentration (MIC) of phosvitin for \textit{S. enterica} was 80 mg/ml.

Growth of \textit{L. monocytogenes} increased rapidly in control broth; the OD of the culture increased from 0.1 (at 7h) to greater than 0.6 (at 18h). As observed with \textit{Salmonella} all phosvitin concentrations inhibited growth of \textit{L. monocytogenes} with higher concentrations causing greater growth inhibition. Greater extensions of the lag phase were observed with increased phosvitin concentrations. Phosvitin at 80 and 100 mg/ml was bacteriostatic to \textit{L. monocytogenes} and the MIC of phosvitin for this pathogen was also 80 mg/ml.

**Inhibitory effect of carvacrol in BHI broth.** Growth of \textit{S. enterica} and \textit{L. monocytogenes} in BHI supplemented with various concentrations of carvacrol is shown in Figures 3 and 4, respectively. For \textit{S. enterica} the OD of control increased from 0.1 to greater than 1.0 within 16 hours. Of all carvacrol concentrations tested, increases in OD were only observed in cultures with the two lowest concentrations (0.09 and 0.12 mg/ml). At 24 hours the OD values of control, and BHI broth with 0.09 mg/ml and 0.12 mg/ml were 1.03, 0.68 and 0.39, respectively. All other concentrations (0.14 to 0.75 mg/ml) of carvacrol completely inhibited growth of \textit{S. enterica}. The MIC of carvacrol for \textit{S. enterica} was 0.14 mg/ml. Except for 0.09 and 0.12 mg/ml, all other carvacrol concentrations tested completely prevented an increase in OD of \textit{L. monocytogenes} cultures. Broth with 0.09 mg/ml had little or no effect on the growth of this pathogen; increases in OD were very similar to that of the control. The MIC of carvacrol for \textit{L. monocytogenes} was 0.14 mg/ml.
Antibacterial effect of phosvitin and carvacrol in soup at 12 °C. The total phenolic content of the 1% solution of carvacrol was 0.98 catechin equivalents. This result coincides with the manufacturer’s claim of “up to 98% total polyphenols”. The initial pH of the soup was 6.1 and water activity 0.994. Tables 2 and 3 show viable counts of *S. enterica* and *L. monocytogenes*, respectively, in onion mushroom soup (12 °C) with phosvitin, carvacrol, or combinations of those antimicrobials. The initial viable count of *S. enterica* or *L. monocytogenes* in soup was ~ 10^5 CFU/ml. For both pathogens the initial viable counts in control soup declined slightly after two days of storage; 0.38- and 0.40-log decreases were observed for *S. enterica* and *L. monocytogenes*, respectively. All antimicrobial treatments tested decreased viable counts of both pathogens after two days of storage.

In control soup viable counts of *S. enterica* increased from 4.60 log CFU/ml (day 2) to 6.95 log CFU/ml at day 8 (Table 2). Phosvitin (60 mg/ml) or carvacrol (0.20 or 0.40 mg/ml) inhibited growth of this pathogen; viable counts (log CFU/ml) at day 8 of storage were 5.28, 4.99, and 2.27 respectively, in soup containing phosvitin (60 mg/ml), carvacrol (0.20 mg/ml) and carvacrol (0.40 mg/ml). The combination of phosvitin (60 mg/ml) and carvacrol (0.40 mg/ml) exerted the greatest cidal effect against *S. enterica* at day 2; viable counts were decreased by 3.91 log. From day 4 through day 8 viable counts of the pathogen were undetected (< 10 CFU/ml); however, results of enrichment tests performed on the soup samples were positive for the pathogen (data not shown).

Viable numbers of *L. monocytogenes* increased from 4.62 log CFU/ml (day 2) to 8.72 log CFU/ml at day 8 in control soup. In soup that contained phosvitin (60 mg/ml) initial numbers of the pathogen were decreased by 1.05 log at day 2 and survivors increased slowly
to reach 5.37 log CFU/ml at day 8. Carvacrol at 0.20 mg/ml reduced initial counts of *L. monocytogenes* by 1.1 log CFU/ml; however, survivors grew relatively fast and reached counts of 8.81 log CFU/ml at day 8. Viable counts (log CFU/ml) at day 8 for the remaining 4 treatments were 4.77 (0.40 mg/ml carvacrol), 4.38 (60 mg/ml phosvitin + 0.20 mg/ml carvacrol), and 3.17 (60 mg/ml phosvitin + 0.40 mg/ml carvacrol).

**Antibacterial effect of phosvitin and carvacrol in soup at 35 °C.** Log reduction in the initial viable count of *S. enterica* following 4 hours of exposure to antimicrobials in onion mushroom soup at 35 °C is shown in Figure 5. The pathogen grew in control soup and in soup with added phosvitin (60 mg/ml) or the lower concentration of carvacrol (0.20 mg/ml). Soup with carvacrol (0.40 mg/ml), 60 mg/ml phosvitin + 0.20 mg/ml carvacrol), or 60 mg/ml phosvitin + 0.40 mg/ml carvacrol exhibited a cidal effect on the pathogen; initial viable counts (control 7.63 log CFU/ml) were reduced by 5.48, 4.48, and 7.33, respectively (P<0.05).

Tables 4 and 5 show the viability of *S. enterica* and *L. monocytogenes* respectively, in onion mushroom soup (35 °C) with added phosvitin (60 mg/ml), carvacrol (0.20 or 0.40 mg/ml) or their combinations. In control soup viable numbers of *S. enterica* increased from 7.63 log CFU/ml at 4 hours to 11.31 log CFU/ml at 24 hours. Compared to control, phosvitin significantly inhibited growth of the pathogen up to 12 hours at 35 °C (P<0.05). Of the two concentrations of carvacrol tested the lower one (0.20 mg/ml) did not significantly inhibit growth of the pathogen in the soup for 24 hours (P>0.05). In fact, viable counts (log CFU/ml) of the pathogen in soup with 0.20 mg/ml carvacrol increased from 6.39 at 4 hours to 10.14 in 24 hours (Table 4). However, when 0.20 mg/ml carvacrol was used in
combination with phosvitin, a much stronger inhibitory effect against the pathogen was observed compared to that produced by phosvitin or carvacrol (0.20 mg/ml) used singly (P<0.05). The extent of growth inhibition produced by that combination of phosvitin and carvacrol was similar to that observed with the higher concentration of carvacrol (0.40 mg/ml). Phosvitin combined with 0.40 mg/ml carvacrol exhibited the greatest cidal effect against S. enterica (P<0.05); no viable counts of the pathogen could be detected in the soup from 8 to 24 hours (Table 4). In all instances when no viable counts were detected by plating, enrichment tests gave positive results for presence of the pathogen (data not shown).

Viable numbers of L. monocytogenes in control soup increased from 4.60 log CFU/ml at 4 hours to 8.01 log CFU/ml at 24 hours (Table 5). Phosvitin suppressed the growth of L. monocytogenes throughout the duration of the study and its inhibitory effect was significantly greater from that of the control from 8 to 24 hours (P<0.05). Compared to control, carvacrol (0.20 mg/ml) alone did not significantly inhibit growth of L. monocytogenes (P>0.05). The higher concentration of carvacrol (0.40 mg/ml) and both phosvitin/carvacrol combinations tested significantly inhibited growth of the pathogen from 8 to 24 hours (P<0.05).

Phosvitin plus carvacrol (0.20 mg/ml) was able to suppress growth of the pathogen until 24 hours of incubation. The combination of phosvitin and carvacrol (0.40 mg/ml) was significantly different from the control after 4 hours. This combination caused a decline in viability of the pathogen in the soup at 35 °C which is highly conducive to prolific growth of the pathogen throughout storage.

Discussion

The application of naturally derived antimicrobials in foods is gaining increasing
attention from the food industry as consumers become concerned over possible negative health effects from long-term consumption of synthetic food preservatives. Certain naturally-derived organic compounds have good potential for use in inhibiting microbial growth or destroying foodborne organisms to extend the microbial shelf-life of foods (27). Based on the results of the present study of phosvitin used alone or combined with carvacrol to control foodborne pathogens in a food product offers further evidence on the antibacterial potential of these compounds.

While there is a growing body of knowledge on the antimicrobial effects of carvacrol, there is a scarcity of published reports on the antimicrobial effects of phosvitin. Also, there are no published reports on the combined antibacterial effectiveness of phosvitin and carvacrol against foodborne human enteric pathogens. In the present study phosvitin strongly inhibited growth of both *S. enterica* and *L. monocytogenes* in BHI broth at 35 °C (Figures 1 and 2). Plate counts to determine numbers of viable pathogens in BHI with phosvitin at the minimum inhibitory concentration (MIC) for each organism (80 mg/ml) revealed that phosvitin exerted a bacteriostatic effect on both pathogens (data not shown). This observed inhibition is likely due to phosvitin binding divalent metal ions such as iron (30) which is an essential mineral for microbial growth (15). Approximately ninety-five percent of iron in hen’s egg yolk is strongly bound by phosvitin in a stable conformation to avoid being used by microbes (13). Such iron ligation can result in suppression of microbial growth in the hen’s egg to protect the developing chick embryo from microbial attack.

Compared to phosvitin, carvacrol completely inhibited growth of *S. enterica* and *L. monocytogenes* at a far lower concentration (MIC = 0.014 mg/ml) (Figs 3 and 4). Plate
counts on cultures of the pathogens in BHI broth with MIC of carvacrol revealed that this antimicrobial was bactericidal; viable numbers of both pathogens decreased over time (data not shown). The antibacterial effectiveness of carvacrol against \textit{S. enterica} and \textit{L. monocytogenes} has been previously reported (17, 35, 36, 53). The MIC of carvacrol observed for \textit{S. enterica} in the present study is within the same range reported in previous studies (28) although higher MICs have been reported (5). Variations in MICs may be attributed to variables such as strain of the organisms tested, type of growth medium and temperature, and potency of the antimicrobial.

The main focus of this study was to determine the antimicrobial activity of phosvitin combined with carvacrol against \textit{S. enterica} and \textit{L. monocytogenes} in an actual food system namely, onion mushroom soup. Considering the fact that improper temperature control can compromise the microbial safety of foods we intentionally held the soup at two abusive temperatures (12 °C and 35 °C). At those temperatures the antimicrobial efficacy of phosvitin alone or combined with carvacrol was evaluated. Holding soup at 12 °C simulates possible temperature conditions in a defective refrigerator that fails to maintain safe temperatures (≤ 4.4 °C). Holding the soup at 35 °C simulates improper temperature control during hot holding especially if there is a failure of hot holding equipment to maintain temperatures at 60 °C or higher. Also, 35 °C is within the optimum growth range of both pathogens. Both \textit{Salmonella} and \textit{Listeria} grew very well in soup at 12 °C (Tables 2 and 3) and at 35 °C (Tables 4 and 5) indicating the potential of this food product to cause foodborne illness although it contains onion powder and garlic powder on the label (Table 1). Both onion and garlic are known to contain antimicrobials including allicin (27); however, it is
likely that the amount of allicin in the soup is at miniscule levels because both onion powder and garlic powder are minor ingredients as shown on the label (Table 1).

Based on the FDA Food Code potentially hazardous foods should not be held for more than four hours between 4.4 °C and 60 °C (9). In that temperature range called the “temperature danger zone”, foodborne pathogens can multiply rapidly. For example, in the present study S. enterica reached 7.63 log CFU/ml of soup within 4 hours in soup held at 35 °C (Table 4). This relatively rapid growth in onion mushroom soup represented approximately 2.63 log increase from the initial population (log 5.0 CFU/ml) of this pathogen. A recent recall of onion soup/dip mix because of contamination with Salmonella (17) reinforces the need for antimicrobial interventions to ensure the microbial safety of these potentially hazardous products.

The observed variability in antimicrobial effectiveness of phosvitin or carvacrol used singly in soup reinforces the fact that combined use of antimicrobials offers a more effective approach for controlling pathogens in foods (25). In this regard the best and most reliable antimicrobial treatment was a combination of phosvitin (60 mg/ml) and carvacrol (0.40 mg/ml) which maintained consistent control of both pathogens irrespective of temperature. The results of this study further emphasize the potential of using phosvitin in combination with other naturally derived antimicrobials to enhance its efficacy in controlling foodborne pathogens. The antimicrobial effectiveness observed from the combined use of phosvitin and carvacrol could allow the use of lower concentrations of each antimicrobial for improved food preservation. However, it is well accepted that the practical application of such
preservative systems would require further research on their impact on the sensory properties of foods.

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    temperature and binding to food components inhibit the antibacterial activity of carvacrol


<table>
<thead>
<tr>
<th>Ingredients in dehydrated onion and mushroom soup/dip mix.</th>
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<tbody>
<tr>
<td>Cornstarch</td>
</tr>
<tr>
<td>Dehydrated onions</td>
</tr>
<tr>
<td>Salt</td>
</tr>
<tr>
<td>Monosodium glutamate</td>
</tr>
<tr>
<td>Maltodextrin</td>
</tr>
<tr>
<td>Wheat flour</td>
</tr>
<tr>
<td>Dehydrated mushrooms</td>
</tr>
<tr>
<td>Partially hydrogenated soybean oil</td>
</tr>
<tr>
<td>Hydrolyzed protein (corn, soy, wheat)</td>
</tr>
<tr>
<td>Autolyzed yeast extract</td>
</tr>
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<td>Caramel color</td>
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<tr>
<td>Onion powder</td>
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<tr>
<td>Guar gum</td>
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<tr>
<td>Garlic powder</td>
</tr>
<tr>
<td>Natural flavors</td>
</tr>
<tr>
<td>Disodium guanylate</td>
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<tr>
<td>Disodium inosinate</td>
</tr>
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</table>

*Sodium 700 mg - 29%

* Ingredients are listed in the same order as they appear on the label of the package.
FIGURE 1. Growth of *Salmonella enterica* in BHI broth (35 °C) supplemented with various concentrations of phosvitin.
FIGURE 2. Growth of Listeria monocytogenes in BHI broth (35 °C) supplemented with various concentrations of phosvitin.
FIGURE 3. Growth of Salmonella enterica in BHI broth (35 °C) supplemented with various concentrations of carvacrol.
FIGURE 4. Growth of *Listeria monocytogenes* in BHI broth (35 °C) supplemented with various concentrations of carvacrol.
FIGURE 5. *Log reduction in initial count of Salmonella enterica following 4 hr of exposure to antimicrobials in onion mushroom soup at 35 °C.*
### TABLE 2. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against Salmonella enterica in onion mushroom soup held at 12 ºC for 8 days.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>2d</th>
<th>4d</th>
<th>6d</th>
<th>8d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.60 ± 0.05ax</td>
<td>6.26 ± 2.51ax</td>
<td>6.02 ± 3.44ax</td>
<td>6.95 ± 3.62ax</td>
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<tr>
<td>Phosvitin (60)</td>
<td>4.42 ± 0.34ax</td>
<td>4.53 ± 0.14abx</td>
<td>4.49 ± 0.42ax</td>
<td>5.28 ± 1.59ax</td>
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<td>Carvacrol (0.20)</td>
<td>3.81 ± 0.20abx</td>
<td>5.24 ± 2.52abx</td>
<td>4.36 ± 3.86ax</td>
<td>4.99 ± 3.39ax</td>
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<td>Carvacrol (0.40)</td>
<td>1.38 ± 2.40bcx</td>
<td>1.75 ± 3.03abx</td>
<td>2.21 ± 3.83ax</td>
<td>2.27 ± 3.93ax</td>
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<tr>
<td>Phos + Car (0.20)</td>
<td>2.75 ± 0.75abcx</td>
<td>2.36 ± 0.32abx</td>
<td>2.49 ± 0.28ax</td>
<td>1.90 ± 0.44ax</td>
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<tr>
<td>Phos + Car (0.40)</td>
<td>0.51 ± 0.89cx</td>
<td>0.00 ± 0.00bx</td>
<td>0.00 ± 0.00ax</td>
<td>0.00 ± 0.00ax</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment*

a,b,c Means with a different letter within a column differ significantly (P<0.05)

x,y,z Means with a different letter within a row differ significantly (P<0.05)
TABLE 3. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against *Listeria monocytogenes* in onion mushroom soup held at 12 °C for 8 days.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>2d</th>
<th>4d</th>
<th>6d</th>
<th>8d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.62 ± 1.14az</td>
<td>5.86 ± 1.12ayz</td>
<td>7.22 ± 0.07axy</td>
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<td>Phosvitin (60)</td>
<td>3.95 ± 0.69ax</td>
<td>4.02 ± 0.63ax</td>
<td>4.80 ± 0.46bcx</td>
<td>5.37 ± 1.33abx</td>
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<tr>
<td>Carvacrol (0.20)</td>
<td>3.90 ± 0.08az</td>
<td>5.60 ± 2.13ayz</td>
<td>7.16 ± 0.75abxy</td>
<td>8.81 ± 0.18ax</td>
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<tr>
<td>Carvacrol (0.40)</td>
<td>4.13 ± 0.40ax</td>
<td>4.31 ± 1.09ax</td>
<td>4.49 ± 1.57cx</td>
<td>4.77 ± 2.11bx</td>
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<tr>
<td>Phos + Car (0.20)</td>
<td>3.94 ± 0.75ax</td>
<td>3.96 ± 0.78ax</td>
<td>4.25 ± 0.56cx</td>
<td>4.38 ± 0.47bx</td>
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<td>Phos + Car (0.40)</td>
<td>3.78 ± 0.70ax</td>
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<td>3.17 ± 1.61bx</td>
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*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

*a,b,c* Means with a different letter within a column differ significantly (P<0.05)

*x,y,z* Means with a different letter within a row differ significantly (P<0.05)
TABLE 4. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against Salmonella enterica in onion mushroom soup held at 35 ºC for 24 hours.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>Viable count (Log_{10} CFU/ml)³</th>
<th>4h</th>
<th>8h</th>
<th>12h</th>
<th>24h</th>
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<tbody>
<tr>
<td>Control</td>
<td></td>
<td>7.63 ± 0.31a</td>
<td>9.46 ± 1.29ax</td>
<td>10.28 ± 0.26awx</td>
<td>11.31 ± 0.02aw</td>
</tr>
<tr>
<td>Phosvitin (60)</td>
<td></td>
<td>5.52 ± 0.95by</td>
<td>6.95 ± 0.51bxy</td>
<td>8.12 ± 0.50bx</td>
<td>10.99 ± 0.03aw</td>
</tr>
<tr>
<td>Carvacrol (0.20)</td>
<td></td>
<td>6.39 ± 0.39abz</td>
<td>8.13 ± 0.01abxy</td>
<td>8.85 ± 0.15abx</td>
<td>10.14 ± 0.17w</td>
</tr>
<tr>
<td>Carvacrol (0.40)</td>
<td></td>
<td>2.15 ± 0.60cx</td>
<td>2.42 ± 1.02cx</td>
<td>3.54 ± 1.12cw</td>
<td>6.65 ± 0.96bw</td>
</tr>
<tr>
<td>Phos + Car (0.20)</td>
<td></td>
<td>3.15 ± 0.56cx</td>
<td>3.12 ± 0.22cx</td>
<td>4.07 ± 1.15cx</td>
<td>6.46 ± 1.26bw</td>
</tr>
<tr>
<td>Phos + Car (0.40)</td>
<td></td>
<td>0.33 ± 0.58dw</td>
<td>0.00 ± 0.00dw</td>
<td>0.00 ± 0.00dw</td>
<td>0.00 ± 0.00cw</td>
</tr>
</tbody>
</table>

³Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

ᵃ,b,c Means with a different letter within a column differ significantly (P<0.05)

w,x,y,z Means with a different letter within a row differ significantly (P<0.05)
TABLE 5. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against Listeria monocytogenes in onion mushroom soup held at 35 ºC for 24 hours.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>4h</th>
<th>8h</th>
<th>12h</th>
<th>24h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.60 ± 0.03a</td>
<td>6.04 ± 0.74ay</td>
<td>6.51 ± 0.24ay</td>
<td>8.01 ± 0.52ax</td>
</tr>
<tr>
<td>Phosvitin (60)</td>
<td>4.22 ± 0.25ax</td>
<td>4.42 ± 0.11bcx</td>
<td>4.68 ± 0.19bx</td>
<td>5.15 ± 0.85bcx</td>
</tr>
<tr>
<td>Carvacrol (0.20)</td>
<td>4.71 ± 0.63az</td>
<td>5.60 ± 0.55abyz</td>
<td>6.40 ± 0.45axy</td>
<td>7.57 ± 0.06abx</td>
</tr>
<tr>
<td>Carvacrol (0.40)</td>
<td>4.11 ± 0.71ax</td>
<td>4.19 ± 0.63bcx</td>
<td>4.27 ± 0.53bx</td>
<td>4.47 ± 0.18cdx</td>
</tr>
<tr>
<td>Phos + Car (0.20)</td>
<td>3.99 ± 0.70ax</td>
<td>4.17 ± 0.44cx</td>
<td>4.33 ± 0.32bx</td>
<td>4.29 ± 0.62cdx</td>
</tr>
<tr>
<td>Phos + Car (0.40)</td>
<td>3.42 ± 0.15ax</td>
<td>3.35 ± 0.36cx</td>
<td>3.23 ± 0.30cx</td>
<td>2.13 ± 1.84dx</td>
</tr>
</tbody>
</table>

Viable count (Log₁₀ CFU/ml) x

Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment

a,b,c Means with a different letter within a column differ significantly (P<0.05)

x,y,z Means with a different letter within a row differ significantly (P<0.05)
CHAPTER 4

GROWTH INHIBITION OF *STAPHYLOCOCCUS AUREUS*, *ESCHERICHIA COLI* O157:H7, AND BACKGROUND MICROFLORA BY PHOSVITIN AND CARVACROL ADDED TO ONION MUSHROOM SOUP

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Key words: *Staphylococcus, Escherichia coli*, phosvitin, carvacrol, soup
Abstract

The antibacterial efficacy of phosvitin, or carvacrol alone, or combined against *Staphylococcus aureus* and *Escherichia coli* O157:H7 in brain heart infusion (BHI) broth and onion mushroom soup was investigated. Broth with added phosvitin (10 - 100 mg/ml), carvacrol (0.09 - 0.75 mg/ml) or combinations was inoculated with *S. aureus* or *E. coli* O157:H7. Broth or soup without antimicrobials served as control. Growth curves and minimum inhibitory concentrations (MICs) for the pathogens in BHI (35 °C, 24 hours) were obtained by using a Bioscreen C turbidometer (OD 600nm). Growth of the pathogens in soup (12 °C, 8 days) and (35 °C, 24 hours) was monitored by surface plating the samples on appropriate selective agar. The MIC of phosvitin and carvacrol was greater than 100 mg/ml and 0.12 mg/ml, respectively, for *S. aureus*; and 80 mg/ml and 0.12 mg/ml, respectively, for *E. coli*. No growth of *S. aureus* occurred in control or treated soup at 12 °C. Phosvitin (60 mg/ml) plus carvacrol (0.40 mg/ml) exhibited the greatest cidal effect against both pathogens, after day 2. With this combination, pathogens were undetected (<10 CFU/ml) from day 4 through day 8. In soup (35 °C, 24hr), phosvitin (60 mg/ml) and carvacrol (0.40 mg/ml) combination reduced viable cells of *S. aureus* and *E. coli* by 6.78 and 9.89 log CFU/ml, respectively. Phosvitin concentration alone, carvacrol (0.40 mg/ml) alone, and in combination were also effective towards growth inhibition of soup background microflora. The combination of phosvitin (60 mg/ml) and carvacrol (0.40 mg/ml) is highly effective for controlling *S. aureus* and *E. coli* in temperature abused onion mushroom soup and has good potential for improving the microbial safety of this potentially hazardous food product during temperature abuse.
Introduction

Control of human enteric foodborne pathogens to prevent of foodborne related illnesses is a goal of the government, food manufacturers, processors and retailers. The continued use of synthetic chemical preservatives to enhance microbial safety of control food has increased consumer health concerns, even though the use of these preservatives may be regarded as safe by regulatory authorities (Beuchat 2008). In this regard, food manufacturers are searching for new naturally derived alternatives to address the concern of consumers. To reduce chemical preservatives that are currently used in foods the following must be addressed when considering substitution with natural antimicrobials: assurance of microbiological food safety, efficacy and functionality in foods; toxicology and safety in food formulations; interactions with food components and other preservatives. Other important considerations include: mechanism of action against microorganisms; influence on food quality and sensory; extraction and isolation methods, and economical production on an adequate scale (Sofos and others 1998; Beuchat 2008). Naturally derived antimicrobials are obtained from either animal, plant, or microbial sources.

Phosvitin is a naturally derived phosphoprotein from egg yolk, containing approximately 120 phosphoserine residues (Castellanie and others 2004). The high phosphorus content allows phosvitin to bind up to 60 iron molecules, dependent on the isolation method (Mecham and Olcott 1949; Taborsky 1963; Webb and others 1973; Albright and others 1984). The ability of phosvitin to remove essential nutrients such as iron from the environment is believed to inhibit growth of foodborne pathogens (Sattar Khan and others 2000). To date, antimicrobial efficacy of phosvitin has been reported in one published paper
In that study *Escherichia coli* was inactivated when subjected to phosvitin (0.1 mg/ml) combined with heat (50 °C, 20 min) (Sattar Khan and others 2000).

Carvacrol, (2-methyl-5-(1-methylethyl)-phenol), is an essential oil from the leaves and flowering plant of both oregano (*Origanum vulgare*) and thyme (*Thymus vulgaris*) (Burt, 2004; Oussalah 2007). The percent composition of carvacrol in oregano ranges from trace amounts to 82% and 2 to 45% in thyme (Lagouri and others 1993; Arrebola and others 1994; Burt 2004). Antimicrobial activity of carvacrol has been studied extensively in broth model systems as well as several foods including: cheese (Smith-Palmer and others 2001), apple cider (Friedman and others 2004, Kisko and Roller 2005), fruit (kiwi and melon) (Roller and Seedhar 2002), carrot broth (Valero and Salmeron 2003), salad (Koutsoumanis and others 1999), lettuce and spinach leaves (Obaidat and Frank 2009), rice (Ultee and others 2000b), turkey (Juneja and Friedman 2007), meat (Veldjuizen and others 2007; Juneja and Friedman 2008; Solomakos and others 2008; Friedman and others 2009), fish/seafood (Kim and others 1995; Meljlholm and Dalgaard, 2002; Ravishankar and others 2010). It has been shown to have stronger antimicrobial effect with increased temperature and storage time, and at a lower pH (Burt 2004; Friedman and others 2004). This phenolic compound is thought to exert antibacterial action by causing structural and functional damage to cellular membranes (Sikkema and others 1995; Sivropoulou and others 1996; Ultee and others 1999). While there is a growing body of knowledge on the antimicrobial effects of carvacrol, against various foodborne pathogens, such published research involving phosvitin is scarce. To our knowledge there are no published research involving the combined use of phosvitin and carvacrol against *Staphylococcus aureus* and *Escherichia coli* O157:H7. The objectives of the present study were: 1) to establish the minimum inhibitory concentration of both
phosvitin and carvacrol in brain heart infusion broth and 2) to evaluate the antimicrobial efficacy of phosvitin, low concentrations of carvacrol both individually and their combinations against foodborne human enteric pathogens and background microflora in soup held at 12 °C and 35 °C.

**Materials and Methods**

**Bacterial cultures and culture conditions**

Three strains of *Staphylococcus aureus* (ATCC 6538, ATCC 25923, and BAA-44) and five strains of *Escherichia coli* O157:H7 (FRIK125, ATCC 35150, ATCC 43894, ATCC 43895, and 93-062) were used in the present study. All cultures were obtained from the culture collection of the Microbial Food Safety Laboratory, Iowa State University, Ames, IA. Stock cultures were kept frozen (-70 °C) in Brain Heart Infusion (BHI) broth (Difco, Becton, Dickinson, Sparks, MD) supplemented with 10% (vol/vol) glycerol. Stock cultures were activated in BHI broth (pH 7.2) and incubated at 35 °C. At least two consecutive 18 to 22-h transfers of each stock culture were carried out before using the cells as inocula in each experiment.

**Preparation of inoculum**

An equal volume of each of the working cultures of *S. aureus* or *E. coli* O157:H7 were combined in a sterile centrifuge tube. The cells were harvested by centrifugation (10,000 x g, 10 min, 4 °C) using a Sorvall Super T21 (American Laboratory Trading, Inc., East Lyme, CT) and washed once in 0.1% (wt/vol) peptone. The pelleted cells were suspended in fresh 0.1% (wt/vol) peptone to obtain a final viable cell concentration of
approximately $10^9$ CFU ml$^{-1}$. Viable counts of the washed cell suspensions were evaluated by surface plating serially diluted (10-fold) samples on tryptic soy agar supplemented with 0.6% yeast extract. The individual cell suspensions were used to inoculate BHI broth or commercial onion mushroom soup.

**Antimicrobials**

Phosvitin was supplied by Dr. Dong Ahn from the Animal Science Department at Iowa State University, Ames, IA. A commercial preparation of carvacrol was purchased from Sigma-Aldrich (Aldrich W224502).

**Total phenolic content of carvacrol**

The concentration of total phenolics of carvacrol was determined using the method described by Waterman and Mole (1994). The assay involves reduction of ferric iron to the ferrous state by phenolic compounds that results in the formation of the Prussian blue complex $\text{Fe}_4\text{[Fe(CN)6]}_3$ with a potassium ferricyanide reagent. The Prussian blue complex is determined colorimetrically (Khiyami and others 2005). Two separate 1% (vol/vol) solutions of carvacrol in 10% (vol/vol) ethanol and deionized water were prepared. The absorbance of three sub-samples from each solution was measured at 720 nm and the total phenolic content expressed as the number of catechin equivalents x 100.

**Preparation of treatment solutions for Bioscreen C assay**

BHI broth with added phosvitin (10, 20, 40, 60, 80, 100 mg/ml) or carvacrol (0.09, 0.12, 0.14, 0.19, 0.38, or 0.75 mg/ml) were filter sterilized using 0.22 µm pore size Millipore filters (Fisher Scientific, Pittsburgh, PA). Samples (2.5-ml) of the treatment solutions and
control (BHI with no added antimicrobial) were each inoculated with 25 µl of diluted (1:100) S. aureus or E. coli O157:H7 cell suspension to obtain a final concentration of approximately $10^5$ CFU/ml of sample.

**Bioscreen C assay**

Aliquots (200 µl) of inoculated samples were added in triplicate to the wells of microtiter plate for the Bioscreen C Turbidometer (Growth Curves, Piscataway, NJ), an automated microbial growth analyzer and incubator. Plates were incubated in the Bioscreen C at 35 °C for 24 h and the instrument was programmed to take optical density (OD) measurements at 600 nm every 30 min, with shaking of samples before each OD reading. Minimum inhibitory concentration (MIC) was defined as the lowest treatment concentration that completely inhibited microbial growth for 24 hr (< 0.05 OD unit increase).

**Preparation and inoculation of soup**

Dehydrated onion mushroom soup/dip mix was purchased from a local grocery store. The soup mix was hydrated with sterile distilled water and prepared according to the directions stated on the package. Soup ingredients are shown in Table 1. After boiling, the soup was tempered to ~ 35 °C and 10-ml portions of the soup were aseptically transferred into sterile 30 ml screw cap Pyrex tubes. Phosvitin, carvacrol or combinations were added to each tube to give the following concentrations: phosvitin (60 mg/ml), carvacrol (0.20 mg/ml or 0.40 mg/ml), phosvitin (60 mg/ml) + carvacrol (0.20 mg/ml) and phosvitin (60 mg/ml) + carvacrol (0.40 mg/ml). Phosvitin was added to the tubes prior to the addition of the soup to prevent aggregation and facilitate its dissolving in the soup. Tubes of soup without added
antimicrobial served as control. The tubes of soup were then warmed or cooled to the desired temperature (12 °C or 35 °C). Tubes of soup with added antimicrobials were mixed by vortexing and inoculated with a suspension of washed cells of the foodborne pathogens to give a final cell concentration of approximately $10^5$ CFU/ml for each pathogen. After inoculation, each tube of soup was gently mixed by vortexing and held at either 12 °C or 35 °C.

**Microbiological analysis**

Inoculated tubes of soup held at 12 °C were tested for survivors of the pathogens every 2 days for a total of 8 days whereas, soup held at 35 °C were tested at 4, 8, 12 and 24 h. Ten-fold serial dilutions of the soup were prepared using 0.1% (vol/vol) peptone with added Tween 80 (0.5% v/v). Aliquots (1.0 ml or 0.1ml) of the soup or diluted samples of soup were surface plated (in duplicate) on mannitol salt agar (for *S. aureus*) and sorbitol MacConkey agar (for *E.coli*). All inoculated plates were incubated at 35 °C for 48h before counting bacterial colonies.

**Measurement of pH and water activity**

The initial pH and water activity of each sample of soup including controls were measured at day 0 (prior to inoculation). Measurements of pH were also taken periodically during storage of the soup at 12 °C or 35 °C. Measurements of pH were taken using an Orion Model 525 pH meter (Orion Research, Inc., Boston, Massachusetts) fitted with a glass electrode. Water activity measurements were taken using the Aqualab CX2 water activity meter (Decagon Services, Pullman, Washington).
Statistical analysis

Three independent replications of each experiment were performed. Mean numbers of survivors *S. aureus* or *E.coli* O157:H7 were statistically analyzed using SAS statistical software version 8.1 (SAS Institute Inc., Cary, N.C.). Treatment means were evaluated for statistically significant differences using Tukey’s test. Significant differences were defined at P < 0.05 for all the experimental data.

Results

Growth inhibition by phosvitin in BHI broth

The effect of phosvitin on the growth of *Staphylococcus aureus* and *Escherichia coli* O157:H7 in Brain Heart Infusion (BHI) broth is shown in Figures 1 and 2. For *S. aureus*, the optical density (OD) of control and broth containing 10 and 20 mg/ml phosvitin increased rapidly and slightly exceeded an OD of 0.8 after 17 hours. Growth inhibition and extension of the lag phase of *S. aureus* increased with higher phosvitin concentrations. The MIC of phosvitin for *S. aureus* was greater than 100 mg/ml. For *E. coli* O157:H7, the OD of the culture increased from 0.1 (at 3h) to greater than 1.2 (at 17h). All phosvitin concentrations, except 10 mg/ml, inhibited growth of *E. coli* O157:H7 with higher concentrations causing more pronounced growth inhibition. Phosvitin at 80 and 100 mg/ml were bacteriostatic. Greater extensions of the lag phase and lower maximum OD values were observed with increased phosvitin concentrations. The MIC of phosvitin for *E. coli* O157:H7 was 80 mg/ml.
Growth inhibition by carvacrol in BHI broth

Growth of *S. aureus* and *E. coli* O157:H7 in BHI supplemented with various concentrations of carvacrol is shown in Figures 3 and 4. The OD of control increased from 0.1 to greater than 0.6 within 18 hours. Increase in OD occurred only in BHI containing 0.09 mg/ml carvacrol. At 24 hours the control and carvacrol (0.09 mg/ml)-containing cultures achieved an OD > 0.7 and 0.45, respectively. All other concentrations of carvacrol (0.12 - 0.75 mg/ml) completely inhibited growth of the organism. The MIC of carvacrol for *S. aureus* was 0.12 mg/ml. Except for 0.09 mg/ml, all other carvacrol concentrations tested against *E. coli* O157:H7 completely inhibited growth of the pathogen. Brain heart infusion broth with 0.09 mg/ml decreased the growth of the pathogen compared to control. At 18 hours the OD of control and carvacrol (0.09 mg/ml) was ~ 1.0 and 0.65, respectively. The MIC of carvacrol for *E. coli* O157:H7 was 0.12 mg/ml.

Growth inhibition by phosvitin and carvacrol in onion mushroom soup at 12 °C

The total phenolic content of the 1% solution of carvacrol was 0.98 catechin equivalents. This result coincides with the manufacturer’s claim of “up to 98% total polyphenols”. The initial pH and water activity of the soup was 6.1 and 0.994, respectively. The initial viable count of *S. aureus* or *E. coli* O157:H7 in onion mushroom soup was Log 5.0 CFU/ml. Viable counts of *S. aureus* or *E. coli* O157:H7 in soup (12 °C) with phosvitin alone or combined with carvacrol are shown in Tables 2 and 3. No growth of *S. aureus* occurred in control or treated soup at 12 °C. In control soup viable numbers of *S. aureus* decreased by 0.86 Log CFU/ml at 4 days and numbers of surviving bacteria remained constant throughout the storage period. Numbers of survivors in soup with phosvitin (60
mg/ml) or carvacrol (0.20 mg/ml) alone were not significantly (P>0.05) different from those in control soup. Carvacrol (0.40 mg/ml) and phosvitin (60 mg/ml) plus carvacrol (0.20 or 0.40 mg/ml) decreased cell survival during the storage period. The combination of phosvitin and carvacrol (0.40 mg/ml) was cidal to S. aureus; initial counts decreased by 4.32 log CFU/ml at 2 days of storage. Viable counts of the pathogen decreased further and were undetectable (<10 CFU/ml) from day 4 to day 8.

In control soup at 12 °C viable numbers of E. coli O157:H7 increased to 6.90 log CFU/ml at day 8. Phosvitin (60mg/ml) exerted a bacteriostatic action on the pathogen; no growth occurred throughout the duration of the study. At day 2, carvacrol (0.20 mg/ml) caused about a 1 log reduction in viable counts compared to the control, and number of survivors remained constant up to 8 days. By day 2, carvacrol (0.40 mg/ml) alone and the combination of phosvitin and carvacrol (0.40mg/ml) caused a log reduction of 2.39 and 4.05, respectively. After day 2 viable cells were undetected (<10 CFU/ml) in soup that contained either of the two treatments.

**Growth inhibition by phosvitin and carvacrol in onion mushroom soup at 35 ºC**

Tables 4 and 5 show the effect of phosvitin, carvacrol and combinations against S. aureus and E. coli O157:H7 in onion mushroom soup (35 °C). In control soup viable numbers of S. aureus increased from 5.60 log at 4 hours to 8.83 log CFU/ml at 24 hours of incubation (Table 4). Compared to control, phosvitin alone strongly inhibited growth of the pathogen for 12 hours (P<0.05). Carvacrol (0.20 mg/ml) alone failed to suppress the growth of the pathogen; however, when it was combined with phosvitin the growth inhibitory effect of that combination was significantly (P<0.05). Viable counts in soup that contained carvacrol
(0.4 mg/ml) alone and the combination of phosvitin and carvacrol (0.40 mg/ml) were significantly (P< 0.05) lower than from the control after 4 hours; however, there was no significant difference between these two treatments (P >0.05). At 24 hours carvacrol (0.40 mg/ml) and phosvitin plus carvacrol (0.40 mg/ml) reduced cell survival by 6.33 and 6.78 log CFU/ml, respectively.

Viable numbers of *E. coli* O157:H7 in control soup increased from 7.59 log at 4 hours to 10.69 log CFU/ml at 24 hours of incubation (Table 5). Viable counts of the pathogen in soup with added phosvitin (60 mg/ml), carvacrol (0.2 or 0.4 mg/ml) and their combinations were significantly (P<0.05) lower than those of the control for the first four hours of incubation at 35°C. Phosvitin strongly inhibited the growth of the microorganisms for the first 8 hours. Carvacrol (0.20 mg/ml) lost effectiveness to suppress the growth of *E. coli* O157:H7 at 8 hours whereas, carvacrol (0.40mg/ml) alone or phosvitin combined with carvacrol (0.20 mg/ml) was effective in suppressing growth of the pathogen within that 8-hour period. Viable counts of soup with the combination of phosvitin and 0.4mg/ml of carvacrol were significantly (P< 0.05) lower than those of control throughout the entire storage period. Phosvitin combined with the highest level of carvacrol (0.40 mg/ml) produced a 9.89 log reduction in viable counts at 24 hours, compared to the control.

In addition to the antimicrobial activity of phosvitin and carvacrol against *S. aureus* and *E. coli*, growth inhibition of background microflora present in soup at 35°C for 12 hours (Figure 5) was evaluated. Background microflora in control soup increased from 1.4 log CFU/ml at time 0 to 4.28 log at 12 hours. At 12 hour, phosvitin (60 mg/ml), carvacrol (0.40 mg/ml), and their combination were significantly (P<0.05) different from the control.
Phosvitin alone, carvacrol alone, and the phosvitin carvacrol combination reduced microflora by 1.39, 2.78, and 3.19 log CFU/ml, respectively.

Discussion

In recent years consumer awareness of food safety has increased substantially. Also consumers are demanding more natural food preservatives instead of synthetic ones. Such changes in consumer attitude are rapidly affecting the actions of the food industry. Food processors are now seeking naturally derived antimicrobials to substitute for currently used synthetic additives. Some naturally-derived antimicrobials include plant essential oils (EO) and their components (Burt, 2004). One component of EO that has very good antimicrobial activity is carvacrol. In the present study we used carvacrol and phosvitin (an antimicrobial protein from egg yolk) to control *S. aureus* and *E. coli* O157:H7 in an onion mushroom soup held at abusive temperatures. While several studies have been published to demonstrate the antibacterial efficacy of carvacrol, to date there is only one published report on the antibacterial effect of phosvitin (Sattar Khan and others 2000). In the present study phosvitin inhibited the growth of *S. aureus* and *E. coli* O157:H7 in BHI broth in a dose dependent manner (Figures 1 and 2). *E. coli* O157:H7 seemed to be more sensitive to phosvitin compared to *S. aureus*. This observed sensitivity might be due to the relatively strong chelation ability of phosvitin (Sattar Khan and others 2000). Carvacrol proved to be a more potent antimicrobial compared to phosvitin due to the very low concentrations required to inhibit the pathogens tested in BHI broth the present study.

It is generally well recognized that concentrations of antimicrobials that are effective in laboratory media require higher concentrations to be effective in actual food products.
Certain antimicrobials, such as essential oils, or their components, may effectively control microorganisms at concentrations that alter sensory quality. To circumvent this issue of high concentration, it might be best to use essential oils in system of antimicrobials consistent with hurdle technology concept (Adams and others 2003; Nychas and Skandamis 2003; Roller and Board 2003). In the present study we were able to use relatively low concentrations (0.20 and 0.40 mg/ml) of carvacrol were combined with phosvitin to control pathogens in onion mushroom soup held at abusive temperatures. Veldhuizen et al. (2007) reported reduced antimicrobial activity of similar concentrations of carvacrol when combined with egg yolk. Our data show that phosvitin alone extracted from the egg yolk actually increased the efficacy of carvacrol. In all instances the combination proved to strongly inhibitory and at times cidal to the pathogens (Tables 2 and 3). We intentionally held the soup at 12 °C and 35 °C to simulate temperature abuse situations. Both of these temperatures fall within the temperature danger zone in which pathogenic bacteria can grow rapidly and reach high populations within 4 hours. At both temperatures the combination of carvacrol and phosvitin was very effective in controlling S. aureus and E. coli O157:H7 in the soup. That combination also inhibited growth of background microflora in onion mushroom soup. Based on these findings the combination of phosvitin and carvacrol has good potential for enhancing the microbial safety of onion mushroom soup and preventing microbial spoilage of this product. Further research is needed to determine the influence of combined antimicrobials on the sensory characteristics and quality of food.

**Acknowledgments**

The authors thank Dr. Bill Collona on his instruction on the use of the bioscreen
and use of the anaerobic chamber. The authors also thank Michael Mendonca and David Manu for laboratory assistance.

References


TABLE 1. *Ingredients in dehydrated onion and mushroom soup/dip mix.*

<table>
<thead>
<tr>
<th>Ingredients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornstarch</td>
</tr>
<tr>
<td>Dehydrated onions</td>
</tr>
<tr>
<td>Salt</td>
</tr>
<tr>
<td>Monosodium glutamate</td>
</tr>
<tr>
<td>Maltodextrin</td>
</tr>
<tr>
<td>Wheat flour</td>
</tr>
<tr>
<td>Dehydrated mushrooms</td>
</tr>
<tr>
<td>Partially hydrogenated soybean oil</td>
</tr>
<tr>
<td>Hydrolyzed protein (corn, soy, wheat)</td>
</tr>
<tr>
<td>Autolyzed yeast extract</td>
</tr>
<tr>
<td>Caramel color</td>
</tr>
<tr>
<td>Onion powder</td>
</tr>
<tr>
<td>Guar gum</td>
</tr>
<tr>
<td>Garlic powder</td>
</tr>
<tr>
<td>Natural flavors</td>
</tr>
<tr>
<td>Disodium guanylate</td>
</tr>
<tr>
<td>Disodium inosinate</td>
</tr>
</tbody>
</table>

*Sodium 700 mg~ 29%

* Ingredients are listed in the same order as they appear on the label of the package
Figure 1. Growth of *Staphylococcus aureus* in BHI broth (35 °C) supplemented with various concentrations of phosvitin.
Figure 2. Growth of *Escherichia coli* O157:H7 in BHI broth (35 °C) supplemented with various concentrations of phosvitin.
Figure 3. Growth of *Staphylococcus aureus* in BHI broth (35 °C) supplemented with various concentrations of carvacrol.
FIGURE 4. Growth of *Escherichia coli* O157:H7 in BHI broth (35 °C) supplemented with various concentrations of carvacrol.
FIGURE 5. The effect of phosvitin (60 mg/ml), carvacrol (0.40 mg/ml) and their combinations against background microflora in soup at 35 °C.
TABLE 2. *Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against Staphylococcus aureus* in onion mushroom soup held at 12 °C for 8 days.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>2d</th>
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<th>6d</th>
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</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.02 ± 0.54ax</td>
<td>4.16 ± 0.20aby</td>
<td>4.29 ± 0.05ax</td>
<td>4.32 ± 0.25axy</td>
</tr>
<tr>
<td>Phosvitin (60)</td>
<td>3.76 ± 0.67abx</td>
<td>3.79 ± 0.44abx</td>
<td>3.60 ± 0.48axx</td>
<td>3.40 ± 0.32abxy</td>
</tr>
<tr>
<td>Carvacrol (0.20)</td>
<td>4.55 ± 0.05axx</td>
<td>4.36 ± 0.92axxx</td>
<td>3.97 ± 0.51axxy</td>
<td>3.88 ± 0.71abxxy</td>
</tr>
<tr>
<td>Carvacrol (0.40)</td>
<td>2.70 ± 0.49bxx</td>
<td>2.59 ± 1.03bxxy</td>
<td>2.05 ± 0.63bxzy</td>
<td>0.80 ± 0.72cxxy</td>
</tr>
<tr>
<td>Phos + Car (0.20)</td>
<td>3.81 ± 0.60abxy</td>
<td>3.47 ± 0.49abxy</td>
<td>3.19 ± 0.63abxyz</td>
<td>2.68 ± 0.77bxxyz</td>
</tr>
<tr>
<td>Phos + Car (0.40)</td>
<td>0.68 ± 1.18cxxy</td>
<td>0.00 ± 0.00cxxxyz</td>
<td>0.00 ± 0.00cxxxyz</td>
<td>0.00 ± 0.00cxxxyz</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment*

*a,b,c* Means with a different letter within a column differ significantly (P<0.05)

*x,y,z* Means with a different letter within a row differ significantly (P<0.05)
TABLE 3. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against *Escherichia coli O157:H7* in onion mushroom soup held at 12 °C for 8 days.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>2d</th>
<th>4d</th>
<th>6d</th>
<th>8d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.80 ± 0.20ax</td>
<td>5.66 ± 1.18ax</td>
<td>6.74 ± 3.37ax</td>
<td>6.90 ± 3.47ax</td>
</tr>
<tr>
<td>Phosvitin (60)</td>
<td>4.45 ± 0.74ax</td>
<td>4.54 ± 0.38abx</td>
<td>4.50 ± 0.32abx</td>
<td>4.62 ± 0.84ax</td>
</tr>
<tr>
<td>Carvacrol (0.20)</td>
<td>3.82 ± 0.36abx</td>
<td>3.67 ± 1.53abx</td>
<td>3.63 ± 3.71abx</td>
<td>3.09 ± 5.35ax</td>
</tr>
<tr>
<td>Carvacrol (0.40)</td>
<td>2.41 ± 0.74bx</td>
<td>0.00 ± 0.00cy</td>
<td>0.00 ± 0.00by</td>
<td>0.00 ± 0.00ay</td>
</tr>
<tr>
<td>Phos + Car (0.20)</td>
<td>3.79 ± 0.52abx</td>
<td>2.99 ± 0.36bx</td>
<td>1.70 ± 1.87abx</td>
<td>1.20 ± 2.08ax</td>
</tr>
<tr>
<td>Phos + Car (0.40)</td>
<td>0.75 ± 0.77cx</td>
<td>0.00 ± 0.00cx</td>
<td>0.00 ± 0.00bx</td>
<td>0.00 ± 0.00ax</td>
</tr>
</tbody>
</table>

* Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment

* Means with a different letter within a column differ significantly (*P*<0.05)

* Means with a different letter within a row differ significantly (*P*<0.05)
TABLE 4. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against *Staphylococcus aureus* in onion mushroom soup held at 35 °C for 24 hours.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>4h</th>
<th>8h</th>
<th>12h</th>
<th>24h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.60 ± 0.58az</td>
<td>7.2 ± 0.58ay</td>
<td>8.28 ± 0.74axy</td>
<td>8.83 ± 0.25ax</td>
</tr>
<tr>
<td>Phosvitin (60)</td>
<td>4.38 ± 0.88ax</td>
<td>4.78 ± 1.22bx</td>
<td>5.07 ± 1.54bcx</td>
<td>6.06 ± 1.44abx</td>
</tr>
<tr>
<td>Carvacrol (0.20)</td>
<td>4.96 ± 0.69ay</td>
<td>6.08 ± 0.62abx</td>
<td>6.77 ± 0.57abx</td>
<td>7.48 ± 0.24abx</td>
</tr>
<tr>
<td>Carvacrol (0.40)</td>
<td>4.15 ± 0.86ax</td>
<td>4.05 ± 0.80bx</td>
<td>3.85 ± 0.94cx</td>
<td>2.50 ± 0.35cdx</td>
</tr>
<tr>
<td>Phos + Car (0.20)</td>
<td>4.11 ± 0.88ax</td>
<td>4.43 ± 0.96bxy</td>
<td>4.03 ± 1.09bcx</td>
<td>5.00 ± 1.94bcx</td>
</tr>
<tr>
<td>Phos + Car (0.40)</td>
<td>3.69 ± 1.03ax</td>
<td>3.72 ± 0.85bx</td>
<td>3.51 ± 1.07cx</td>
<td>2.05 ± 0.56dx</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment*

*a,b,c* Means with a different letter within a column differ significantly (*P*<0.05)

*x,y,z* Means with a different letter within a row differ significantly (*P*<0.05)
TABLE 5. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with carvacrol against *Escherichia coli* O157:H7 in onion mushroom soup held at 35 °C for 24 hours.

<table>
<thead>
<tr>
<th>Treatment (mg/ml)</th>
<th>4h</th>
<th>8h</th>
<th>12h</th>
<th>24h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.59 ± 0.07az</td>
<td>9.62 ± 0.30ay</td>
<td>9.99 ± 0.12ay</td>
<td>10.69 ± 0.27ax</td>
</tr>
<tr>
<td>Phosvitin (60)</td>
<td>4.54 ± 0.95bcy</td>
<td>5.29 ± 1.51bcy</td>
<td>6.12 ± 0.05aby</td>
<td>9.23 ± 0.17ax</td>
</tr>
<tr>
<td>Carvacrol (0.20)</td>
<td>4.98 ± 0.36z</td>
<td>8.32 ± 0.05aby</td>
<td>9.23 ± 0.11ax</td>
<td>8.89 ± 0.08ax</td>
</tr>
<tr>
<td>Carvacrol (0.40)</td>
<td>2.35 ± 0.82cdx</td>
<td>3.89 ± 2.16cdx</td>
<td>4.37 ± 3.79bcx</td>
<td>5.43 ± 4.71abx</td>
</tr>
<tr>
<td>Phos + Car (0.20)</td>
<td>4.52 ± 0.81bcx</td>
<td>4.63 ± 0.84cdx</td>
<td>5.44 ± 1.43abcx</td>
<td>5.11 ± 4.43abx</td>
</tr>
<tr>
<td>Phos + Car (0.40)</td>
<td>1.58 ± 1.37dx</td>
<td>1.32 ± 1.22dx</td>
<td>1.26 ± 1.20cx</td>
<td>0.80 ± 0.72bx</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

Means with a different letter within a column differ significantly (P<0.05).

Means with a different letter within a row differ significantly (P<0.05).
CHAPTER 5

THE ANTIMICROBIAL EFFECT OF PHOSVITIN, NISIN AND COMBINATION AGAINST SALMONELLA ENTERICA, ESCHERICHIA COLI O157:H7 AND STAPHYLOCoccus AUREUS IN A COMMERCIAL TYPE SOUP AT 12 °C AND 35 °C

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Key words: Salmonella, Escherichia, Staphylococcus, phosvitin, nisin, soup
Abstract

The objective of this research was to identify antimicrobial activities of phosvitin, or nisin alone, or in combination against *Salmonella enterica*, *Escherichia coli* O157:H7 and *Staphylococcus aureus* in brain heart infusion (BHI) broth and abused soup held at unsafe temperatures. Broth supplemented with phosvitin (10 - 100 mg/ml), nisin (500 or 1000 IU) or combinations was inoculated (10^5 CFU/ml) with *S. enterica*, *E. coli* O157:H7 or *S. aureus*. Broth or soup without antimicrobials served as control. Growth of *S. enterica*, *E. coli*, and *S. aureus* in BHI (35 °C, 24 hours) was monitored using a Bioscreen C turbidometer (OD 600nm). Growth of the pathogens in soup (12 °C, 8 days and 35 °C, 24 hours) were monitored by surface plating. In BHI broth minimum inhibitory concentration (MIC) of phosvitin was 80 mg/ml for both *S. enterica* and *E. coli* O157:H7 and greater than 100 mg/ml for *S. aureus*. Phosvitin at the concentration range of 20-100 mg/ml inhibited growth of *S. enterica* and *E. coli* O157:H7; 80 mg/ml was bacteriostatic for both organisms. *S. aureus* was less sensitive to phosvitin compared to the two Gram-negative pathogens. For *S. enterica* and *E. coli* O157:H7 control cultures grew rapidly in soup and reached about 6.90 log CFU/ml in 8 days.

Phosvitin inhibited growth of *S. enterica* and *E. coli* O157:H7 for 6 and 8 days, respectively whereas, nisin (1000 IU) was ineffective in preventing growth of those pathogens. No growth of *S. aureus* occurred in control or treated soup at 12 °C. Irrespective of storage temperature (12 °C or 35 °C), phosvitin combined with either concentration of nisin did not offer enhanced antibacterial effect above that provided by phosvitin used alone.
Introduction

Foodborne illnesses caused by human enteric pathogens such as *Salmonella enterica*, *Escherichia coli* O157:H7 and *Staphylococcus aureus* are a significant problem and cause major health concerns annually (Mead et al., 1999). For several decades synthetic food preservatives such as nitrites, sulfites, and parabens have been used to control foodborne pathogens and spoilage microorganisms (Jay, 2005). The extensive use of synthetic chemicals for antimicrobial or other functions has resulted in the widespread movement towards use of natural antimicrobials as consumers become more health conscious. The food industry is looking to use “natural”, cost efficient antimicrobials from plant, microbial and/or animal sources, as replacements. The use of hurdle technology will allow natural antimicrobials to be combined, increasing microbial safety, decreasing high individual concentrations and widening the spectrum of antimicrobial activity (Leistner, 2000).

Phosvitin is a metal chelating protein found in egg yolk. Egg yolk participates in embryonic development by providing essential nutrients for the developing embryo. Phosvitin, a 35 kDa phosphoglycoprotein, is the major egg yolk protein. It is currently recognized as the most phosphorylated protein in nature. Over half of the amino acids present in phosvitin are serine, of which 90% are phosphorylated (Taborsky, 1983; Byrne et al., 1984; Clark, 1985). The numerous phosphorylated serine residues have a strong affinity for divalent metals and contribute to the chelating ability of phosvitin (Osaki et al., 1975; Grogan and Taborsky, 1987). This property allows binding to nutrients in the environment and binding to membranes of bacteria. To date there is only one published paper addressing
the antimicrobial properties of phosvitin (Sattar Khan et al., 2000). These authors found that the combination of phosvitin and heat (50 °C) inactivated *Escherichia coli* O157:H7.

Nisin, is produced as a defense response to some lactic acid bacteria (LAB), specifically *Lactococcus lactis* subspecies *lactis*. To date, nisin is the only Generally Recognized As Safe (GRAS) commercially available bacteriocin approved for use as a preservative additive in over fifty countries (FAO/WHO, 1969; FDA, 1988; Jay, 2000). Nisin has been used as a natural antimicrobial peptide and is bactericidal against some strains of following Gram-positive bacteria: *Alicyclobacillus* (Komitopoulou et al., 1999), *Bacillus* (Jaquette and Beuchat, 1998), *Brochothrix* (Cutter and Siragusa, 1996), *Clostridium* (Okereke and Montville, 1992), *Enterococcus* (Laukova, 1995), *Lactobacillus* (Chun and Hancock, 2000) *Listeria* (Knight et al., 1999), *Micrococcus* (Dutreux et al., 2000), and *Staphylococcus* (Thomas and Wimpenny, 1996). Nisin is unable to penetrate the cell wall of yeast and Gram-negative bacteria (Kordel et al., 1989; Boziaris and Adams, 1999). In susceptible vegetative cells the primary site of action by nisin is the cytoplasmic membrane (Abee et al., 1995; Kuwano et al., 2005). This bacteriocin has the ability to bind to the membrane and form pores that destroy the membrane integrity. Pore formation leads to leakage of K+ ions and ATP, depletion of the proton motive force, and depolarization of transmembrane potential, resulting in cell death (Sahl, 1991; Bruno and Montville, 1993; Millette et al., 2004).

While there is an extensive knowledge base on the antimicrobial effects of nisin against various foodborne pathogens, such published research involving phosvitin is scarce. In fact there is only one published paper on the effects of phosvitin on *E. coli* O157:H7 (Sattar Khan, 2000). Also, to our knowledge there is no published research involving the
combined use of phosvitin and nisin against *Salmonella enterica*, *Escherichia coli* O157:H7, or *Staphylococcus aureus*. The first objective of the present study was to establish the minimum inhibitory concentration of phosvitin and nisin for *S. enterica*, *E. coli* O157:H7 and *S. aureus* in laboratory broth medium. The second objective was to evaluate the antimicrobial effectiveness of phosvitin, nisin, and their combination against those same foodborne pathogens in a commercial-type onion mushroom soup.

**Materials and Methods**

**Bacterial cultures and culture conditions.** Five serotypes of *Salmonella enterica* (Enteritidis-ATCC13076, Heidelberg, Typhimurium-ATCC 14802, Gaminara-8324, Oranienburg-9329), five strains of *Escherichia coli* O157:H7 (FRIK125, ATCC 35150, ATCC 43894, ATCC 43895, and 93-062) and three strains of *Staphylococcus aureus* (ATCC 6538, ATCC 25923, and BAA-44) were used in the present study. All cultures were obtained from the culture collection of the Microbial Food Safety Laboratory, Iowa State University, Ames, IA. Stock cultures were kept frozen (−70 ºC) in Brain Heart Infusion (BHI) broth (Difco, Becton, Dickinson, Sparks, MD) supplemented with 10% (vol/vol) glycerol. Stock cultures were activated in BHI broth (pH 7.2) and incubated at 35 ºC. At least two consecutive 18 to 22-h transfers of each stock culture were carried out before using the cells as inocula in each experiment.

**Preparation of inoculum.** An equal volume of the individual working cultures of *L. monocytogenes* or *S. enterica* were combined in a sterile centrifuge tube. The cells were harvested by centrifugation (10,000 x g, 10 min, 4ºC) using a Sorvall Super T21 (American
Laboratory Trading, Inc., East Lyme, CT) and washed once in 0.1% (wt/vol) peptone. The pelleted cells were suspended in fresh 0.1% (wt/vol) peptone to obtain a final viable cell concentration of approximately 10^9 CFU ml^{-1}. Viable counts of the washed cell suspensions were evaluated by surface plating serially diluted (10-fold) samples on tryptic soy agar supplemented with 0.6% yeast extract. The individual cell suspensions were used to inoculate BHI broth or commercial onion mushroom soup.

**Antimicrobials.** Phosvitin was supplied by Dr. Dong Ahn from the Animal Science Department at Iowa State University, Ames, IA. Nisin was purchased from Danisco (Nisaplin, Danisco Cultor USA) and was reported to be 2.5% pure (1000 IU/mg).

**Total phenolic content of carvacrol.** The concentration of total phenolics of carvacrol was determined using the method described by Waterman and Mole (1994). The assay involves reduction of ferric iron to the ferrous state by phenolic compounds that results in the formation of the Prussian blue complex Fe4[Fe(CN)6]3 with a potassium ferricyanide reagent. The Prussian blue complex is determined colorimetrically (Khiyami et al., 2005). Two separate 1% (vol/vol) solutions of carvacrol in 10% (vol/vol) ethanol and deionized water were prepared. The absorbance of three sub-samples from each solution was measured at 720 nm and the total phenolic content expressed as the number of catechin equivalents x 100.

**Preparation of treatment solutions for Bioscreen C assay.** BHI broth with added phosvitin (10, 20, 40, 60, 80, 100 mg/ml) or nisin (500 or 1000 IU) were filter sterilized using 0.22 µm pore size Millipore filters (Fisher Scientific, Pittsburgh, PA). Samples (2.5-ml) of the treatment solutions and control (BHI with no added antimicrobial) were each inoculated with 25 µl of diluted (1:100) *S. enterica*, *E. coli* O157:H7 or *S. aureus* cell
suspension to obtain a final concentration of approximately $10^5$ CFU/ml of sample.

**Bioscreen C assay.** Aliquots (200-µl) of inoculated samples were added in triplicate to the wells of microtiter plate for the Bioscreen C Turbidometer (Growth Curves, Piscataway, NJ), an automated microbial growth analyzer and incubator. Plates were incubated in the Bioscreen C at 35 °C for 24 h and the instrument was programmed to take optical density (OD) measurements at 600 nm every 30 min, with shaking of samples before each OD reading. Minimum inhibitory concentration (MIC) was defined as the lowest treatment concentration that completely inhibited microbial growth for 24 hr (< 0.05 OD unit increase).

**Preparation and inoculation of soup.** Dehydrated onion mushroom soup/dip mix was purchased from a local grocery store. The soup mix was hydrated with sterile distilled water and prepared according to the directions stated on the package. Soup ingredients are shown in Table 1. After boiling, the soup was tempered to ~ 35 °C and 10-ml portions of the soup were aseptically transferred into sterile 30 ml screw cap pyrex tubes. Phosvitin, nisin or combinations were added to each tube to give the following concentrations: phosvitin (60 mg/ml), nisin (500 IU or 1000IU), phosvitin (60 mg/ml) + nisin (500 IU) (*S. aureus* only) and phosvitin (60 mg/ml) + nisin (1000 IU). Phosvitin was added to the tube prior to the addition of the soup to prevent aggregation and facilitate its dissolving in the soup. Tubes of soup without added antimicrobial served as control. The treatments were then warmed or cooled to the target temperature. Tubes of soup with added antimicrobials were mixed by vortexing and inoculated with a suspension of washed cells of the foodborne pathogens to give a final cell concentration of approximately $10^5$ CFU/ml for each pathogen. After
inoculation, each tube of soup was gently mixed by vortexing and held at either 12 °C or 35 °C.

**Microbiological analysis.** Inoculated tubes of soup held at 12 °C were tested for survivors of the pathogens every 2 days for a total of 8 days whereas, soup held at 35 °C were tested at 4, 8, 12 and 24 h. Ten-fold serial dilutions of the soup were prepared using 0.1% (vol/vol) peptone with added Tween 80. Aliquots (1.0 ml or 0.1 ml) of the soup or diluted samples of soup were surface plated (in duplicate) on xylose lysine desoxycolate (XLD) agar (for *S. enterica*), sorbitol MacConkey agar (for *E. coli*) and mannitol salt agar (for *S. aureus*). All inoculated plates were incubated at 35 °C for 48 h before counting bacterial colonies.

**Measurement of pH and water activity.** The initial pH and water activity of each sample of soup including controls was measured at day 0 (prior to inoculation). Measurements of pH were also taken periodically during storage of the soup at 12 °C or 35 °C. Measurements of pH were taken using an Orion Model 525 pH meter (Orion Research, Inc., Boston, Massachusetts) fitted with a glass electrode. Water activity measurements were taken using the Aqualab CX2 water activity meter (Decagon Services, Pullman, Washington).

**Statistical analysis.** Three independent replications of each experiment were performed. Mean numbers of survivors *S. enterica*, *E. coli* O157:H7, or *S. aureus* were statistically analyzed using SAS statistical software version 8.1 (SAS Institute Inc., Cary, N.C.). Treatment means were evaluated for statistically significant differences using Tukey’s test. Significant differences were defined at *P* < 0.05 for all the experimental data.
Results

**Inhibitory effect of phosvitin in BHI broth.** Figures 1, 2 and 3 show the effect of various concentrations of phosvitin on the growth of *S. enterica*, *E. coli* O157:H7 and *S. aureus*, respectively, in Brain Heart Infusion (BHI) broth at 35 °C. The initial OD for all the cultures at time 0 was approximately 0.1. Phosvitin at the concentration range of 20 -100 mg/ml inhibited growth of *S. enterica* and *E. coli* O157:H7; 80 mg/ml was bacteriostatic for both organisms (Figures 1 and 2). Also increased lag phase and lower maximum OD values were observed with increased phosvitin concentrations. Compared to the two Gram-negative pathogens, *S. aureus* was less sensitive to phosvitin. Absolutely no growth inhibition of this pathogen occurred at phosvitin concentrations of 10 and 20 mg/ml. Also, growth of the pathogen occurred at 80 and 100 mg/ml which were bacteriostatic for *S. enterica* and *E. coli* O157:H7.

**Inhibitory effect of phosvitin/nisin combinations in BHI broth.** Figures 4, 5, and 6 show the effect of phosvitin and phosvitin/nisin combinations on growth of *S. enterica*, *E. coli* O157:H7, and *S. aureus* in BHI. Nisin (500 or 1000 IU) was ineffective against *S. enterica* and *E. coli* O157:H7; both pathogens grew equally well in control and in BHI with added nisin. All combinations of phosvitin and nisin were more inhibitory than nisin but similar in inhibitory action to phosvitin alone at the concentration corresponding to the phosvitin in the combination (Figures 4 and 5). For *S. aureus*, nisin (500 and 1000 IU) completely inhibited growth of the organism. Except for 20 mg/ml phosvitin, all other phosvitin concentrations (40 and 60 mg/ml) were growth inhibitory. Combinations of
phosvitin and nisin were less effective than nisin alone but similar in inhibitory action to phosvitin alone at the concentration corresponding to the phosvitin in the combination.

**Antibacterial effect of phosvitin and nisin in soup at 12 °C.** The total phenolic content of the 1% solution of carvacrol was 0.98 catechin equivalents. This result coincides with the manufacturer’s claim of “up to 98% total polyphenols”. The initial pH of the soup was 6.1 and water activity 0.994. Tables 2, 3, and 4 show viable counts of *S. enterica*, *E. coli* O157:H7 and *S. aureus*, respectively, in onion mushroom soup (12 °C) with phosvitin, nisin, or combinations of those antimicrobials. The initial viable count for *S. enterica*, *E. coli* O157:H7, or *S. aureus*, in soup was ~ $10^5$ CFU/ml. For *S. enterica* and *E. coli* O157:H7 control cultures grew rapidly and reached about 6.90 log CFU/ml in 8 days. Phosvitin inhibited growth of *S. enterica* and *E. coli* O157:H7 for 6 and 8 days, respectively whereas, nisin (1000 IU) was ineffective in preventing growth of those pathogens. Viable counts of the pathogens in soup with the combination of phosvitin and nisin were not significantly different from those of control or other treatments (Figures 2 and 3).

No growth of *S. aureus* occurred in control or treated soup at 12 °C. In control soup viable numbers of *S. aureus* decreased and survivors remained constant throughout the storage period. Viable counts of the pathogen in soup with phosvitin (60 mg/ml) were not significantly (P>0.05) different from the control after 2 days. Both nisin (500 and 1000 IU) concentrations alone were significantly different from the control. At day 2 a log reduction of 2.75 and 3.19 was seen for 500 IU and 1000 IU, viable cells continued to decrease a through 8 days. Phosvitin combined with either concentration of nisin similarly increased the effectiveness of phosvitin alone.
Antibacterial effect of phosvitin and nisin in soup at 35 °C. Tables 5, 6, and 7 show the effect of phosvitin, nisin, and combinations against *S. enterica*, *E. coli* O157:H7 and *S. aureus* in onion mushroom soup (35 °C). In control soup viable numbers of *S. enterica* increased from 7.63 log at 4 hours to 11.31 log CFU/ml at 24 hours of incubation. Viable counts of the pathogen in soup with phosvitin alone were significantly (P<0.05) different from those of control for the first 12 hours of the study. Viable counts in soup with nisin (1000 IU) alone were not significantly (P>0.05) different from those of the control. Phosvitin plus nisin (1000 IU) also extended the lag phase of growth and was significantly different from other treatments and control at 24 hours of incubation (Table 5). At 24 hours the viable count of *S. enterica* was 2.16 log CFU/ml less than that of the control.

In control soup viable numbers of *E. coli* O157:H7 increased from 7.59 log at 4 hours to 10.69 log CFU/ml at 24 hours of incubation. Phosvitin (60 mg/ml) was bacteriostatic, limiting the growth of the microorganisms for the first 8 hours. Phosvitin was significantly (P<0.05) different from the control the entire duration of the study. Nisin (1000 IU) alone was similar to the control and was ineffective in growth suppression of *E. coli* O157:H7. The combination of phosvitin and nisin was similar to phosvitin alone for the first 12 hours. At 24 hours, this combination was the most effective reducing cell viability by 2.59 log CFU/ml.

In control soup viable numbers of *S. aureus* increased from 5.60 log at 4 hours to 8.83 log CFU/ml at 24 hours of incubation. Phosvitin alone was bacteriostatic for the first 12 hours, and was significantly (P<0.05) different from the control at 8 and 12 hours of the study. Both nisin (500 and 1000 IU) concentrations and combinations were significantly (P < 0.05) different from the control for up to 12 hours. Nisin (500 and 1000) initially reduced
viable cells by 4 hours, and gradually increased as time progressed over the remaining 18 hours. After 12 hours both nisin concentrations were no longer different from the control, however the two combinations were significantly (P< 0.05) different from the control at 24 hours. Phosvitin combined with nisin 500 IU and nisin 1000 IU reduced survivors by 3.15 and 4.31, respectively, at 24 hours compared to the control.

**Discussion**

Naturally derived antimicrobials for food preservation may be extracted from plant, animal or microbial sources. Examples of such antimicrobials are phosvitin and nisin. Phosvitin is a glycoprotein from egg yolk (Mecham and Olcott, 1949). It is currently known for being the most phosphorylated protein in nature (Taborsky, 1983). Also it is known to have a very strong chelating ability, can bind up to 60 mol of Fe$^{2+}$ per phosvitin molecule (Mecham and Olcott, 1949; Taborsky, 1963; Webb et al., 1973; Albright et al., 1984). Nisin, is a bacteriocin, produced by *Lactococcus lactis* spp. *lactis*. Currently it is the only bacteriocin approved for use in foods. The antimicrobial spectrum of nisin is limited to some species of gram-positive bacteria. It is generally ineffective against Gram-negative bacteria. However, when combined with chelating agents such as ethylenediaminetetraacetic acid (EDTA) enhanced bactericidal effects have been observed (Gill and Holly, 2000; Branen and Davidson, 2004).

In the present study we exploited the metal chelating ability of phosvitin to enhance the activity of nisin. We hypothesized that phosvitin, would destabilize the outer membrane of Gram-negative activity to allow nisin to penetrate the bacterial cell. In this regard, we used a combination of phosvitin and nisin to inhibit growth of pathogens in a laboratory
broth medium and in a commercial-type soup held at abusive temperatures. Phosvitin was inhibitory in a dose dependent manner against *S. enterica, E. coli O157:H7* and *S. aureus* in a laboratory broth medium. Nisin alone was ineffective against the Gram-negative bacteria, as expected. Interestingly the combination of phosvitin and nisin was not effective in inactivating the pathogens. In fact the antimicrobial effect of the combination was quite similar to the effect of phosvitin used alone. The results of the study suggest that the combination of phosvitin and nisin under these circumstances would not be cost efficient, due to possible requirements for higher concentrations of phosvitin to achieve the desired antimicrobial control. However, future studies should be conducted to determine phosvitin mechanism of action and test the efficacy of phosvitin peptides.

References


<table>
<thead>
<tr>
<th>Ingredients in dehydrated onion and mushroom soup/dip mix.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornstarch</td>
</tr>
<tr>
<td>Dehydrated onions</td>
</tr>
<tr>
<td>Salt</td>
</tr>
<tr>
<td>Monosodium glutamate</td>
</tr>
<tr>
<td>Maltodextrin</td>
</tr>
<tr>
<td>Wheat flour</td>
</tr>
<tr>
<td>Dehydrated mushrooms</td>
</tr>
<tr>
<td>Partially hydrogenated soybean oil</td>
</tr>
<tr>
<td>Hydrolyzed protein (corn, soy, wheat)</td>
</tr>
<tr>
<td>Autolyzed yeast extract</td>
</tr>
<tr>
<td>Caramel color</td>
</tr>
<tr>
<td>Onion powder</td>
</tr>
<tr>
<td>Guar gum</td>
</tr>
<tr>
<td>Garlic powder</td>
</tr>
<tr>
<td>Natural flavors</td>
</tr>
<tr>
<td>Disodium guanylate</td>
</tr>
<tr>
<td>Disodium inosinate</td>
</tr>
<tr>
<td>*Sodium 700 mg~ 29%</td>
</tr>
</tbody>
</table>

* Ingredients are listed in the same order as they appear on the label of the package.
Figure 4. Growth of *Salmonella enterica* in BHI broth (35 °C) supplemented with various concentrations of phosvitin.
Figure 2. Growth of *Escherichia coli* O157:H7 in BHI broth (35°C) supplemented with various concentrations of phosvitin.
Figure 3. Growth of *Staphylococcus aureus* in BHI broth (35 °C) supplemented with various concentrations of phosvitin.
Figure 4. The effect of phosvitin combined with nisin against *Salmonella enterica* in BHI broth at 35 °C.
Figure 5. The effect of phosvitin combined with nisin against *Escherichia coli* O157:H7 in BHI broth at 35 °C.
Figure 6. The effect of phosvitin combined with nisin against *Staphylococcus aureus* in BHI broth at 35 °C
TABLE 2. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with nisin against *Salmonella enterica* in onion mushroom soup held at 12 °C for 8 days.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Viable count (Log$_{10}$ CFU/ml)\textsuperscript{x}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2d</td>
</tr>
<tr>
<td>Control</td>
<td>4.60 ± 0.05ax</td>
</tr>
<tr>
<td>Phosvitin (60mg/ml)</td>
<td>4.42 ± 0.34ax</td>
</tr>
<tr>
<td>Nisin (1000 IU)</td>
<td>4.43 ± 0.14ax</td>
</tr>
<tr>
<td>Phos + Nis (1000 IU)</td>
<td>4.49 ± 0.55ax</td>
</tr>
</tbody>
</table>

\textsuperscript{x}Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment

\textsuperscript{a,b,c}Means with a different letter within a column differ significantly (P<0.05)

\textsuperscript{x,y,z}Means with a different letter within a row differ significantly (P<0.05)
TABLE 3. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with nisin against *Escherichia coli* O157:H7 in onion mushroom soup held at 12 °C for 8 days.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2d</th>
<th>4d</th>
<th>6d</th>
<th>8d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.80 ± 0.20ax</td>
<td>5.66 ± 1.18ax</td>
<td>6.74 ± 3.37ax</td>
<td>6.90 ± 3.47ax</td>
</tr>
<tr>
<td>Phosvitin (60mg/ml)</td>
<td>4.45 ± 0.74ax</td>
<td>4.54 ± 0.38ax</td>
<td>4.50 ± 0.32ax</td>
<td>4.62 ± 0.84ax</td>
</tr>
<tr>
<td>Nisin (1000 IU)</td>
<td>4.09 ± 0.09ax</td>
<td>6.07 ± 2.29ax</td>
<td>6.14 ± 3.23ax</td>
<td>6.49 ± 3.81ax</td>
</tr>
<tr>
<td>Phos + Nis (1000 IU)</td>
<td>4.52 ± 0.31ax</td>
<td>4.10 ± 0.22ax</td>
<td>4.16 ± 0.46ax</td>
<td>4.26 ± 0.21ax</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment

\[a,b,c\] Means with a different letter within a column differ significantly \((P<0.05)\)

\[x,y,z\] Means with a different letter within a row differ significantly \((P<0.05)\)
TABLE 4. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with nisin against *Staphylococcus aureus* in onion mushroom soup held at 12 °C for 8 days.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2d</th>
<th>4d</th>
<th>6d</th>
<th>8d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.02 ± 0.54ax</td>
<td>4.16 ± 0.20ay</td>
<td>4.29 ± 0.05axy</td>
<td>4.32 ± 0.25axy</td>
</tr>
<tr>
<td>Phosvitin (60mg/ml)</td>
<td>3.76 ± 0.67bx</td>
<td>3.79 ± 0.44ax</td>
<td>3.60 ± 0.48abx</td>
<td>3.4 ± 0.32abx</td>
</tr>
<tr>
<td>Nisin (500 IU)</td>
<td>2.27 ± 0.52cx</td>
<td>1.9 ± 0.64bcx</td>
<td>2.01 ± 0.31cdx</td>
<td>1.85 ± 0.33cdx</td>
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<tr>
<td>Nisin (1000 IU)</td>
<td>1.83 ± 0.34cx</td>
<td>1.23 ± 1.06cx</td>
<td>1.15 ± 0.99dx</td>
<td>0.93 ± 0.81dx</td>
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<tr>
<td>Phos + Nis (500 IU)</td>
<td>3.05 ± 0.27bcx</td>
<td>2.76 ± 0.28abcx</td>
<td>2.82 ± 0.52bcx</td>
<td>2.65 ± 0.53bcx</td>
</tr>
<tr>
<td>Phos + Nis (1000 IU)</td>
<td>3.02 ± 0.17bcx</td>
<td>2.85 ± 0.20abcx</td>
<td>2.69 ± 0.27bcx</td>
<td>2.48 ± 0.19bcx</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

a, b, c Means with a different letter within a column differ significantly (P<0.05).

x, y, z Means with a different letter within a row differ significantly (P<0.05).
TABLE 5. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with nisin against *Salmonella enterica* in a mushroom/onion soup held at 35 °C for 24 hours.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Viable count (Log$_{10}$ CFU/ml) $^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4h</td>
</tr>
<tr>
<td>Control</td>
<td>7.63 ± 0.31a z</td>
</tr>
<tr>
<td>Phosvitin (60mg/ml)</td>
<td>5.52 ± 0.95b cz</td>
</tr>
<tr>
<td>Nisin (1000 IU)</td>
<td>7.06 ± 0.28a by</td>
</tr>
<tr>
<td>Phos + Nis (1000 IU)</td>
<td>5.08 ± 0.69c cz</td>
</tr>
</tbody>
</table>

$^*$Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

$^{a,b,c}$Means with a different letter within a column differ significantly (P<0.05).

$^{x,y,z}$Means with a different letter within a row differ significantly (P<0.05).
TABLE 6. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with nisin against *Escherichia coli O157:H7* in onion mushroom soup held at 35 ºC for 24 hours.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>4h (Log$_{10}$ CFU/ml)</th>
<th>8h (Log$_{10}$ CFU/ml)</th>
<th>12h (Log$_{10}$ CFU/ml)</th>
<th>24h (Log$_{10}$ CFU/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.59 ± 0.07az</td>
<td>9.62 ± 0.30ay</td>
<td>9.99 ± 0.12ay</td>
<td>10.69 ± 0.27ax</td>
</tr>
<tr>
<td>Phosvitin (60mg/ml)</td>
<td>4.54 ± 0.95by</td>
<td>5.29 ± 1.51by</td>
<td>6.12 ± 1.51by</td>
<td>9.23 ± 0.17bx</td>
</tr>
<tr>
<td>Nisin (1000 IU)</td>
<td>8.15 ± 0.39ay</td>
<td>9.58 ± 0.88ax</td>
<td>10.13 ± 0.07ax</td>
<td>10.65 ± 0.51ax</td>
</tr>
<tr>
<td>Phosvitin + Nisin</td>
<td>4.48 ± 0.51by</td>
<td>5.00 ± 0.86by</td>
<td>5.76 ± 0.48by</td>
<td>8.10 ± 0.20cx</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment*

*a,b,c* Means with a different letter within a column differ significantly (P<0.05)

*x,y,z* Means with a different letter within a row differ significantly (P<0.05)
TABLE 7. Antibacterial effectiveness of phosvitin (60 mg/ml) alone or combined with nisin against Staphylococcus aureus in onion mushroom soup held at 35 °C for 24 hours.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Viable count (Log$_{10}$ CFU/ml)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4h</td>
</tr>
<tr>
<td>Control</td>
<td>5.6 ± 0.58a z</td>
</tr>
<tr>
<td>Phosvitin (60mg/ml)</td>
<td>4.38 ± 0.88abx</td>
</tr>
<tr>
<td>Nisin (500 IU)</td>
<td>3.01 ± 0.98bcy</td>
</tr>
<tr>
<td>Nisin (1000 IU)</td>
<td>1.97 ± 0.94cy</td>
</tr>
<tr>
<td>Phos + Nis (500 IU)</td>
<td>3.76 ± 0.82abcx</td>
</tr>
<tr>
<td>Phos + Nis (1000 IU)</td>
<td>3.46 ± 0.65abcx</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

a,b,c Means with a different letter within a column differ significantly (P<0.05)

x,y,z Means with a different letter within a row differ significantly (P<0.05)
CHAPTER 6

THE DEATH RATE OF FOODBORNE PATHOGENIC BACTERIA EXPOSED TO CARVACROL INCREASES WITH RATE OF CELLULAR LEAKAGE

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Key words: carvacrol, foodborne pathogens, membrane disruption
Abstract

Carvacrol is a plant-derived antimicrobial compound that has strong antibacterial activity. In spite of numerous published research reports on the antimicrobial effectiveness of carvacrol, only few have attempted to elucidate its mechanism of bactericidal action. Washed cells of *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella enterica*, and *Staphylococcus aureus* were suspended to obtain ~ 1 x 10⁸ CFU/ml in 0.6% NaCl (37 °C) containing carvacrol at 0.0 (control), 0.2, and 0.4 mg/ml. At 5-min intervals, suspensions were sterile filtered and each filtrate analyzed for material with A₂₆₀. Viability of the cell suspensions was evaluated by enumeration on both non-selective and selective agars. The cellular death rate was determined by using absorbance and viability data. Cell morphology was evaluated by transmission electron microscopy. For all organisms, A₂₆₀ increased significantly with increased carvacrol concentration and exposure time. Within 0.2 min of exposure to carvacrol (0.4 mg/ml) initial viable numbers of *E. coli* O157:H7 and *L. monocytogenes* decreased by 8.90 and 6.64 Log CFU/ml, respectively. There was a very strong correlation between the initial rate of release of A₂₆₀ and death rate of the pathogens (r = 0.998). At 0.4 mg/ml carvacrol, *E. coli* O157:H7 cells appeared collapsed and showed signs of lysis when observed by transmission electron microscopy. At 0.4 and 0.6 mg/ml carvacrol, *L. monocytogenes* cells showed no physical damage; however, loss of intracellular material was observed by transmission electron microscopy. It was concluded that carvacrol-induced death of foodborne pathogens involves disruption of the cytoplasmic membrane.

Introduction

Changing consumer attitude to the use of synthetic chemicals in foods has fueled
current interest of food manufacturers to seek naturally derived antimicrobial for food applications (Ultee et al., 1998). However, the adoption of naturally-derived antimicrobials by the food industry has been slow due to several issues. The major issues include precise identification of active ingredients and the use of relatively high antimicrobial concentrations that may negatively affect sensory qualities of foods (Nychas, 2003; Roller and Board, 2003). The antimicrobial activity of essential oils has been associated with substituted aromatic molecules such as cinnamaldehyde, eugenol, and carvacrol (Moleyar and Narasimhan, 1992).

To circumvent the issue of high concentrations plant essential oils or their components may be used in a manner consistent with the hurdle technology concept (Adams and Smid, 2003; Blaszyk and Holley, 1998). The production of multicomponent antimicrobial systems for foods calls for a very good understanding of the mechanism of action of specific components. This knowledge can help in focusing on potentially effective combinations.

Antimicrobial effects of essential oils are believed to involve interactions with the cell membrane; however, the actual mechanism of inhibitory action needs to be clarified (Roller and Board, 2003). Experiments on the antimicrobial activity of carvacrol revealed that it possesses a broad spectrum of antimicrobial activity against Gram-positive and Gram-negative bacteria (Fenaroli, 1995). Carvacrol’s antimicrobial activity encompasses inactivation of fungi (Chami et al., 2005; Tampieri et al., 2005), parasites (Lindberg et al., 2000), and insects (Panella et al., 2005). In spite of the large amount of research on carvacrol performed in recent years little is understood in regard to its antibacterial mechanism of action. Based on carvacrol’s hydrophobicity, the bacterial membrane seems to be a likely initial target of this naturally-derived antimicrobial. Ultee et al. (1999) demonstrated that
Carvacrol at 0.25 and 1.0 mM increased cytoplasmic membrane permeability for protons and potassium ions, respectively, in Bacillus cereus. Xu et al. (2008) reported that both carvacrol and thymol increased the permeability of the cytoplasmic membrane of Escherichia coli. More recently La Storia et al. (2011), using atomic force microscopy analysis, demonstrated alterations in surface structure of several carvacrol-treated foodborne bacteria. The main objective of the present study was to determine if the bactericidal effect of carvacrol is linked to cytoplasmic membrane damage in selected foodborne pathogenic bacteria.

**Materials and Methods**

**Bacterial cultures and culture conditions.** Salmonella enterica (Typhimurium-ATCC 14802), Escherichia coli O157:H7 (ATCC 438952) and Listeria monocytogenes (Scott A - NADC-2045 – 4b) and Staphylococcus aureus (ATCC 6538) were used in the present study. All cultures were obtained from the culture collection of the Microbial Food Safety Laboratory, Iowa State University, Ames, IA. Stock cultures were kept frozen (-70 °C) in Brain Heart Infusion (BHI) broth (Difco, Becton, Dickinson, Sparks, MD) supplemented with 10% (vol/vol) glycerol. Stock cultures were activated in BHI broth (pH 7.2) and incubated at 35 °C. At least two consecutive 18 to 22-h transfers of each stock culture were carried out before using the cells as inocula in each experiment.

**Chemicals.** A commercial preparation of carvacrol (Aldrich W224502) and sodium chloride (NaCl) was purchased from Sigma-Aldrich.
Preparation of treatments. Stock solutions of carvacrol (0.20 mg/ml, 0.40 mg/ml) were prepared in 0.6% saline. Each treatment (30 ml) was transferred aseptically into separate, sterile tubes and held at 37 °C for 30 min in a water bath prior to inoculation.

Preparation of cell suspension. Pathogens were grown separately in Erlenmeyer flasks containing 100ml of BHI at 35 °C. After 18 h the cells were harvested by centrifugation in a Beckman J2-21 centrifuge (Beckman Instruments Inc., Palo Alto Calif.) operating at 10,000 x g for 10 min at 4 °C. The cell pellets were resuspended in 0.6% saline to give a final viable cell concentration of approximately 2.0 x 10^10 CFU/ml as determined by plate counts on tryptic soy agar plus yeast extract (TSAYE).

Exposure to treatment. Each tube of prewarmed treatment (carvacrol) was inoculated with 500 µl of cell suspension to give a final concentration of 5.2 x 10^8 CFU/ml. Cells were mixed immediately by vortexing and then held at 37 °C. Note that 12 s elapsed from the time of inoculation of the buffer to the time cells were plated or diluted in buffered peptone water (Difco Laboraroties, Detroit, Mich.); time zero represented approximately 12 s of exposure. At time 0, 5, 10, 15 min, 5ml aliquots of treated cell suspension were removed from the treatment tubes. Of the treated cell suspension 1 ml was added to 9 ml of buffered peptone water and vortexed, then plated onto selective and nonselective agar. Simultaneously, the remaining 4.0 ml of treated cell suspension was filtered through a 25mm diameter Luer Lock plastic syringe. Filtrates were then examined for material with A_260 (206 nm AM).

Measurement of cellular leakage. Leakage of cytoplasmic contents was determined by the detection of 260 nm absorbing material (AM) in the cell filtrates. Quartz cuvettes containing 3 ml of cell filtrate were scanned at wavelengths ranging from 400 to 230 nm at a
scan speed of 500 nm per min using a UV spectrophotometer (Beckman Instruments). All treatments were replicated 3 times.

**Cell viability.** Cell viability was determined by serially diluting treated cells in buffered peptone water followed by surface plating 1.0 ml onto nonselective and selective agar media. TSAYE was used as the nonselective medium. Sorbitol MacConkey agar (Difco Laboratories, Detroit, Mi) and modified Oxford agar (Oxoid/Unipath, Columbia, Md.) were used as selective media for *E. coli* O157:H7 and *L. monocytogenes*.

**Transmission electron microscopy.** Pelleted cells were resuspended in fresh fixative containing 2.5% (vl/vol) glutaraldehyde in 0.1 M SCB and then held at 4 °C for 2 h. The cells were pelleted by centrifugation, washed three times with 0.1 M SCB, and fixed with 1% osmium tetroxide (OsO₄) in 0.1 M SCB for 3 h at 25 °C. After three buffer washes in 0.1 M SCB, the cells were negatively stained and prepared for transmission electron microscopy.

**Statistical analysis.** Three independent replications of each experiment were performed. Mean numbers of survivors *E. coli* O157:H7 or *L. monocytogenes* were statistically analyzed using SAS statistical software version 8.1 (SAS Institute Inc., Cary, N.C.). Treatment means were evaluated for statistically significant differences using Tukey’s test. Significant differences were defined at *P* < 0.05 for all the experimental data.

**Results**

**Effect of carvacrol on cell viability.** The viability of *E. coli* O157:H7 and *L. monocytogenes* decreased as time of exposure to carvacrol increased. Viable counts of *E. coli* O157:H7 in 0.6% saline with added carvacrol (0.4 mg/ml) declined faster than those of
L. monocytogenes at that same concentration of carvacrol (Fig. 1 and 2). After 0.2 min, the death rate (Log_{10} reductions per min) of both E. coli O157:H7 and L. monocytogenes decreased (Fig. 1 and 2).

**Leakage of cytoplasmic constituents.** At carvacrol concentrations of 0.2, 0.4, and 0.8 mg/ml leakage of 260 nm absorbing material (AM) from E. coli O157:H7, L. monocytogenes, S. enterica, and S. aureus increased with time. The amount of 260 nm AM released from those organisms also increased as carvacrol concentration increased (Table 1). There was a strong correlation (R^2 = 0.9981) between leakage of 260 nm AM and death rate of the cells.

**Effect of carvacrol on cell microtopography.** Cells of E. coli O157:H7 that were exposed to 0.4, and 0.6 mg/ml carvacrol appear wrinkled and collapsed (Fig. 4 C and D) whereas L. monocytogenes cells exposed to those same carvacrol concentrations retained their shape (Fig. 5 C and D). Loss of intracellular material was seen in cells of E. coli O157:H7 (Figure 6 B and C) and L. monocytogenes exposed to 0.4 and 0.6 mg/ml carvacrol.

**Discussion**

There is rapidly increasing trend towards the use of plant-derived antimicrobials. One such antimicrobial is carvacrol, which is part of the essential oil fractions of oregano (60 to 70% carvacrol) and thyme (45% carvacrol). The antimicrobial effectiveness of carvacrol has been previously reported (Lambert et al., 2001; Valero and Frances, 2006). Carvacrol’s mechanism of antibacterial action has been purportedly associated with damage of the cytoplasmic membrane (Ultee et al., 1999, 2002; Ousslah et al., 2006). While various
carvacrol concentrations have been reported to cause cytoplasmic membrane damage, to date no research has correlated the extent of carvacrol induced membrane damage (as evidenced by leakage of 260 nm AM) with bacterial death rate. The rapid death of both *E. coli* O157:H7 and *L. monocytogenes* in 0.0.6% saline during exposure to relatively low concentrations of carvacrol (0.2 or 0.4 mg/ml) reflects the bactericidal characteristic of carvacrol. While the viable numbers of both pathogens rapidly decreased within 0.2 min, *E. coli* O157:H7 exhibited a greater sensitivity to carvacrol compared to *L. monocytogenes*. *E. coli* O157:H7’s loss of viability seemed greater than that of *L. monocytogenes* at both concentrations of carvacrol tested in the present study. La Storia et al. (2011) also reported that gram negative *E. coli O157:H7* was less resistant to carvacrol exposure. The phenolic component of carvacrol has prompted research focused on its effect on structural and functional damage to cellular membranes (Sikkema et al., 1995, Sivropoulou et al., 1996, Ultee et al., 1999). Several methods have been used to investigate the antibacterial mechanism of action of carvacrol: spectrofluorometry (Ultee et al., 1999, 2002; Lambert, 2001), scanning electron microscopy (Kwon et al., 2003; Di Pasqua et al., 2007), confocal laser scanning microscopy (Gill and Holly, 2006) and flow cytometry (Xu et al., 2008). It is well known that the membrane damaging effects of certain disinfectants such as triclosan, cresol, hexachloaphene against bacteria is due to their phenolic constituents (Bean and Das, 1966; Heath et al., 2000). Damage to the bacterial cytoplasmic membrane can result in leakage of 260 nm absorbing material (AM). In the present study the increased leakage of 260 nm AM from cells of *E. coli* O157:H7, *L. monocytogenes*, *S. enterica*, and *S. aureus* during their exposure to carvacrol indicated that their cytoplasmic membranes endured damage and were unable to retain cytoplasmic constituents. Damage to the cytoplasmic
membrane was consistent with release of 260 nm AM (Fig. 3). The absorption spectra for nucleic acids have a maximum at 260 nm (Ulitzur, 1972); therefore, the 260 nm AM released by carvacrol-treated cells most likely consisted of purines and pyrimidines from the metabolic pool.

Negative stain and transmission electron microscopy provided further evidence for cytoplasmic membrane damage in cells exposed to carvacrol. Carvacrol-treated *E. coli* O157:H7 cells (as seen in transmission electron microscopy photographs) appeared wrinkled, collapsed, and showed loss of cellular constituents compared to control cells (Fig. 4 and Fig. 6). Interestingly, although carvacrol-treated *L. monocytogenes* cells endured damage to the cytoplasmic membrane no signs of wrinkled or collapsed cells were observed in the electron micrographs; however, loss of cellular material was observed in Fig. 7. A plausible explanation for this observation is that *L. monocytogenes* is a Gram-positive bacterium and has a very thick cell wall (peptidoglycan) that better maintain the shape of the cell compared to Gram-negative bacteria such as *E. coli*.

Based on the results of the present study, particularly the very strong correlation ($R^2 = 0.9981$) between leakage of 260 nm AM from carvacrol-treated cells and their death rate, we conclude that carvacrol induced death of foodborne pathogenic bacteria involves disruption of the cytoplasmic membrane.

**Acknowledgments**

The authors thank the Microscopy and NanoImaging Facility (MNIF) staff (Tracy Pepper) at Iowa State University.
References


FIGURE 1. E. coli O157:H7 survivors after exposure to carvacrol in 0.6% saline$^x$.

$^x$Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.
FIGURE 2. *L. monocytogenes* survivors after exposure to carvacrol in 0.6% saline.

Each reported value for viable count represents the mean of three independent replications of the experiment.
**TABLE 1. Effect of varying concentration of carvacrol on DNA leakage of Escherichia coli O157:H7 (ATCC 43895), Listeria monocytogenes (Scott A), Salmonella enterica (Typhimurium) and Staphylococcus aureus (ATCC 6538) in 0.6% saline solution for 15 minutes.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>0.2 m</th>
<th>5m</th>
<th>10m</th>
<th>15m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E. coli O157:H7</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.04 ± 0.00a</td>
<td>0.04 ± 0.00b</td>
<td>0.04 ± 0.00b</td>
<td>0.04 ± 0.00b</td>
</tr>
<tr>
<td>Carvacrol 0.2 mg/ml</td>
<td>0.13 ± 0.08a</td>
<td>0.19 ± 0.14ab</td>
<td>0.34 ± 0.21ab</td>
<td>0.27 ± 0.17b</td>
</tr>
<tr>
<td>Carvacrol 0.4 mg/ml</td>
<td>0.20 ± 0.09a</td>
<td>0.28 ± 0.11a</td>
<td>0.33 ± 0.13ab</td>
<td>0.31 ± 0.17ab</td>
</tr>
<tr>
<td>Carvacrol 0.8 mg/ml</td>
<td>0.17 ± 0.04a</td>
<td>0.23 ± 0.02ab</td>
<td>0.48 ± 0.12a</td>
<td>0.62 ± 0.12a</td>
</tr>
<tr>
<td><strong>L. monocytogenes</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Control</td>
<td>0.03 ± 0.00b</td>
<td>0.03 ± 0.00c</td>
<td>0.03 ± 0.00c</td>
<td>0.03 ± 0.00b</td>
</tr>
<tr>
<td>Carvacrol 0.2 mg/ml</td>
<td>0.23 ± 0.03a</td>
<td>0.21 ± 0.11b</td>
<td>0.20 ± 0.09bc</td>
<td>0.21 ± 0.16b</td>
</tr>
<tr>
<td>Carvacrol 0.4 mg/ml</td>
<td>0.18 ± 0.06a</td>
<td>0.26 ± 0.04ab</td>
<td>0.33 ± 0.13b</td>
<td>0.21 ± 0.70b</td>
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<tr>
<td>Carvacrol 0.8 mg/ml</td>
<td>0.18 ± 0.02a</td>
<td>0.40 ± 0.03a</td>
<td>0.61 ± 0.08a</td>
<td>0.61 ± 0.03a</td>
</tr>
<tr>
<td><strong>S. enterica</strong></td>
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<tr>
<td>Control</td>
<td>0.04 ± 0.00a</td>
<td>0.04 ± 0.00b</td>
<td>0.04 ± 0.00b</td>
<td>0.04 ± 0.00c</td>
</tr>
<tr>
<td>Carvacrol 0.2 mg/ml</td>
<td>0.23 ± 0.17a</td>
<td>0.25 ± 0.15ab</td>
<td>0.30 ± 0.22ab</td>
<td>0.25 ± 0.15bc</td>
</tr>
<tr>
<td>Carvacrol 0.4 mg/ml</td>
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<td>0.27 ± 0.12ab</td>
<td>0.38 ± 0.13a</td>
<td>0.47 ± 0.04b</td>
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<td>Carvacrol 0.8 mg/ml</td>
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<td>0.42 ± 0.02a</td>
<td>0.60 ± 0.02a</td>
<td>0.95 ± 0.23a</td>
</tr>
<tr>
<td><strong>S. aureus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.05 ± 0.00a</td>
<td>0.05 ± 0.00b</td>
<td>0.05 ± 0.00b</td>
<td>0.05 ± 0.00b</td>
</tr>
<tr>
<td>Carvacrol 0.2 mg/ml</td>
<td>0.23 ± 0.10a</td>
<td>0.22 ± 0.13ab</td>
<td>0.30 ± 0.15a</td>
<td>0.35 ± 0.22a</td>
</tr>
<tr>
<td>Carvacrol 0.4 mg/ml</td>
<td>0.14 ± 0.05a</td>
<td>0.29 ± 0.10a</td>
<td>0.26 ± 0.08ab</td>
<td>0.24 ± 0.01ab</td>
</tr>
<tr>
<td>Carvacrol 0.8 mg/ml</td>
<td>0.20 ± 0.11a</td>
<td>0.20 ± 0.02ab</td>
<td>0.24 ± 0.05ab</td>
<td>0.38 ± 0.05a</td>
</tr>
</tbody>
</table>

*Each reported value for viable count represents the mean (standard deviation) of three independent replications of the experiment.

Means with a different letter within a column differ significantly (P<0.05)
FIGURE 3. Relationship between initial rate of leakage of 260 nm AM and death rate for E. coli O157:H7, exposed to 0.20 mg/ml and 0.40 mg/ml carvacrol in 0.6% saline.
FIGURE 4. Negative staining of Escherichia coli O157:H7 control (A) and cells exposed to carvacrol 0.20 mg/ml (B), 0.40 mg/ml (C), and 0.60 mg/ml (D) in 0.6% saline for 15 min.
FIGURE 5. Negative staining of Listeria monocytogenes control (A) and cells exposed to carvacrol, 0.20 mg/ml (B), 0.40 mg/ml (C), and 0.60 mg/ml (D) in 0.6% saline for 15 min.
FIGURE 6. Transmission Electron Microscopy (TEM) of Escherichia coli O157:H7 exposed to carvacrol 0.0 mg/ml (control) (A), 0.4 mg/ml (B), and 0.60 mg/ml (C) in 0.6% saline for 15 min.
FIGURE 7. *Transmission Electron Microscopy (TEM)* of *Listeria monocytogenes* exposed to *carvacrol* 0.0 mg/ml (control) (A), 0.4 mg/ml (B), and 0.60 mg/ml (C) in 0.6% saline for 15 min.
CHAPTER 7. GENERAL CONCLUSIONS

Bacterial pathogens present in food and beverages can infect humans and cause foodborne illnesses. Naturally-derived antimicrobials from plant, animal or microbial sources are gaining increased attention from the food industry as consumers demand more natural food products with no synthetic chemical preservatives.

The present research indicated that combinations of two naturally-derived antimicrobials namely carvacrol (from oregano or thyme) and phosvitin (from egg yolk) are strongly inhibitory to *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella enterica*, and *Staphylococcus aureus* in both laboratory broth media and in onion mushroom soup stored at abusive temperatures (12 and 35 °C). Phosvitin (60 mg/ml) combined with carvacrol (0.4 mg/ml) proved to be the most effective combination for controlling the foodborne pathogens used in the present study. Phosvitin and carvacrol exert a bacteriostatic and bactericidal effect, respectively, against foodborne pathogenic bacteria. Possible mechanism of antibacterial action of carvacrol is linked to cytoplasmic membrane damage.

Phosvitin (60 mg/ml) combined with nisin (1000 IU) does not offer any greater antimicrobial effect than phosvitin used alone against Gram-negative foodborne pathogens in onion mushroom soup held at 12 °C and 35 °C. Further research is needed to address the following: sensory characteristics (organoleptic properties), possible combinations with other hurdle techniques (antimicrobials, high pressure), and optimize combinations in various food products as a natural source of food safety and food preservation.
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First and foremost I would like to thank God for all of my blessings. I would like to thank my parents Edward and Barbara White; brother, Brian Little; sister Chantell White; nephew Sean White-Mcperson and extended family for their continued love and support throughout the course of my degrees.

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