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Novel food processing innovations to improve food safety and health

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Innovazioni nella lavorazione di nuovi prodotti alimentari per migliorare la sicurezza alimentare e la salute

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Summary
Innovative food processing can be used to improve safety of specialty crops and their co-products, while improving sustainability of agricultural and food processing operations and enhancing overall nutritional quality of foods for both domestic and international consumers. The potential of various innovative food processes, many of which have been developed at the USDA, Agricultural Research Service, Western Regional Research Center in Albany, CA, and some of which have been transferred into commercialization through partnerships with industry will be discussed. Innovative technologies such as film casting, ultraviolet, infrared, and solar energy treatments, can enhance final food product quality and nutritional value, while improving food safety. Novel edible films and coatings formulated with natural antibacterial essential oils and food packaging systems to improve food safety will be discussed. Applications of nanoscience to edible films will also be discussed.

Riassunto
Le nuove tecniche di lavorazione dei prodotti alimentari possono essere utilizzate per migliorare la sicurezza delle colture specializzate e dei loro co-prodotti, migliorando nel contempo la sostenibilità delle operazioni di trasformazione agro-alimentare e valorizzando la qualità nutrizionale complessiva dei cibi sia per i consumatori nazionali che internazionali. In questo lavoro si tratterà della potenzialità di queste nuove tecniche, molte delle quali sono state sviluppate presso l'USDA, il Dipartimento Americano per l'Agricoltura, nel centro di ricerca regionale occidentale di Albany, California ed in alcuni casi sono già state commercializzate attraverso partnership con l'industria. Le tecnologie innovative come l'utilizzo di film edibili, i trattamenti con ultravioletti, con infrarossi e con energia solare, possono migliorare la qualità e il valore nutrizionale del prodotto finale, migliorando nel contempo la sicurezza alimentare. Saranno poi trattati i nuovi film edibili e i rivestimenti formulati con oli essenziali antibatterici naturali e i sistemi di confezionamento degli alimenti per migliorarne la sicurezza alimentare. Si affronterà inoltre anche il tema dell'applicazione della nanoscienza ai film edibili.

Introduction

Western Regional Research Center (WRRC) in Albany, CA, is an important branch of the Agricultural Research Service (ARS). The mission of ARS is to conduct research to develop and transfer solutions to agricultural problems of high national priority and provides information access and dissemination to ensure high-quality, safe food and other agricultural products, assess the nutritional needs of Americans, sustain a competitive agricultural economy, enhance the natural resource base and the environment, and provide economic opportunities for rural citizens, communities, and society as a whole. ARS has over 100 research locations in the U.S. with approximately 2050 Lead Scientists. WRRC is known by its contribution of innovations in agricultural research. It has a complete food processing pilot plant to process fruits and vegetables by different separation, concentration, molding, extruding and drying technologies to produce shelf-stable food products.

WHO and FAO stated that low fruit and vegetable intake is a key risk factor for obesity, heart disease and cancer. USDA, ARS has found that people who eat more servings of fruit each day have lower body mass indexes. Studies have also shown that diets high in whole grains and fiber result in lower body mass indexes. There is still room for nutritional improvements, as less than 30% of Americans eat the recommended servings of fruits and vegetables each day. The impact of seven innovative technologies to process fruits and vegetables (forming, casting, coating, extrusion, ultraviolet-B treatment, infrared processing, solar thermal drying) developed by WRRC will be discussed in this presentation in regard to their role to enhance the safety and nutritional value of processed fruits and vegetables.

Forming and extrusion technology

McHugh and Huxsoll (1) investigated the potential of twin screw extrusion technology to produce value-added, restructured peach and peach/starch gels. They determined the effects of water content, melt temperature, sugar and starch concentration on product color, water activity and texture. Water exhibited the greatest effects. As water content increased, product color darkened significantly, water activity increased, and hardness and springiness values decreased significantly in both peach and peach/starch gels. Increasing melt temperatures resulted in darker products. Significant interactions between water content and temperature were observed for 100% peach gels. Starch addition resulted in significant increases in hardness, adhesiveness and cohesiveness values, as well as decreases in product springiness. Increasing melt temperatures resulted in peach/starch gels with softer, more adhesive and cohesive textures. The addition of sugar to peach gels did not significantly affect their color; however, sugar addition did significantly increase the L, a, and b values of peach/starch gels. Sugar concentration did not affect peach gel texture, but sugar and starch concentration interacted significantly in peach/starch gels. As sugar concentration increased, the effect of starch concentration on the hardness and adhesiveness decreased.

Akdogan and McHugh (2) developed a semi-empirical, nonlinear model to incorporate the effects of extruder operating conditions (temperature, moisture, and shear rate) on viscosity of peach puree in a lab-size twin screw extruder. A power law dependency for shear rate, an exponential dependency for moisture, and a modified first order transform function for temperature effects were employed. Motor torque and specific mechanical energy were significantly affected by all extruder operating conditions. Color indicatives (L, a, b) and extrudate density were mainly influenced by the moisture content. Later, Akdogan and McHugh (3) studied the suitability of Bingham, Herschel-Bulkley, Casson, and Mizrahi-Berk models, to characterize the flow behavior of peach products during extrusion. The Casson equation sufficiently described the flow of peach extrudates within the 49 to 125 s^{-1} shear rate range. As concentration increased, yield stress and consistency coefficients increased. A rheological model was proposed to describe the viscosity of peach extrudates. The model incorporated the effect of shear rate by the Casson equation and the effect of concentration by a linear expression. This model provided a good fit to the experimental data for peach extrudates reconstituted from drum-dried peach purees.

McHugh and Huxsoll (4) patented a forming technology to produce 100% fruit bars by using molding extruding. The patent has been used by Gorge Delights, a fruit cooperative in Washington, that uses half million pounds of fresh fruit annually, mostly by molding drum-dried purees from pears, apples, blueberries, cherries, raspberries to produce 500,000 Just Fruit bars and 200,000 other labels annually, that are sold around the globe (Iran, Japan, Mexico, Canada, Peru, etc.). The Processed Foods Research unit at WRRC also is using this forming technology to develop an obesity prevention bar formulated with dried fruits and cereal fiber and a vitamin premix to provide essential nutrients, antioxidants and fiber. These bars are being tested by the Children's Hospital at Oakland Research Institute (CHORI) through a Cooperative Research Agreement with WRRC.

Casting technology

Edible films can control moisture, oxygen, carbon dioxide, flavor and aroma transfer between food components or the atmosphere surrounding the food. Preservatives, acidulants, antioxidants, and antibiotic compounds can be added to edible films to reduce surface microbial populations on foods and enhance oxygen-barrier properties. Edible films can also enhance food nutritional value and improve the appearance of foods. Several reviews are available on edible film and coating systems (5-8). A greater emphasis on safety features associated with the addition of antimicrobial agents is the next area for development in edible films technology (9).

McHugh et al. (10) developed the first edible films made from fruit purees and characterized their water vapor and oxygen permeability properties. Fruit-based edible films were excellent oxygen barriers, particularly at low to moderate relative humidities. McHugh and Senesi (11) coated apple pieces by dipping into solutions and then drying or wrapping in preformed apple-based edible films. Changes in moisture content and color were measured during storage. Increasing concentrations of lipids significantly improved the moisture barrier properties of films. Water vapor permeability varied from 69 to 325 g-mm/kPa-d-m^2. Apple-based wraps significantly reduced moisture loss and browning in fresh-cut apples. Color was preserved for twelve days at 5 °C. Wraps were significantly more effective than coatings of the same composition. Sugars, which are abundant in fruits, can function as plasticizers in edible films (12).

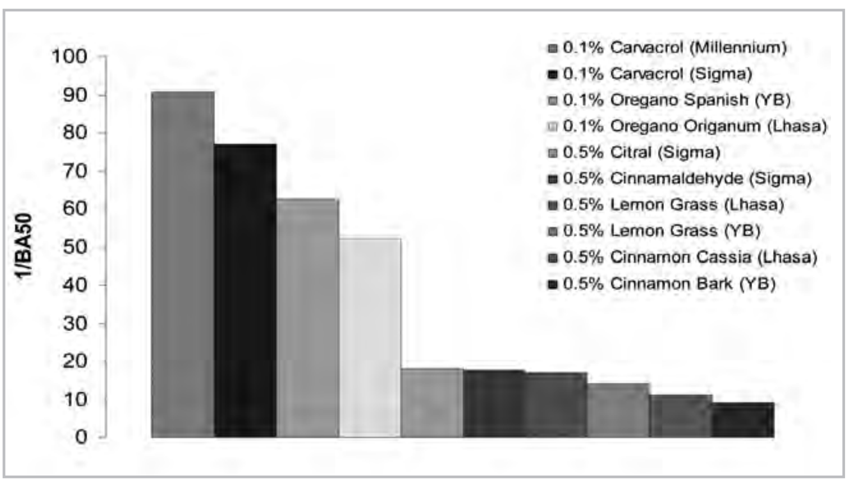
Edible films are commonly produced via a solution casting process where the films are dried from 2 to 12 h. Reductions in drying times enabled the formation of films with no significant microbial contamination. Knowledge of critical control points is necessary to reduce the risk of microbial growth. The quality of the starting materials, as well as the use of heat and good sanitation during casting and drying, are necessary to insure safety (13).

Edible fruit films developed by McHugh and others received a 2001 Best of What's New Award from Popular Science magazine and were the subject of over 100 press reports in that year alone. Interest in the use of fruit and vegetable films is extremely high and recently a commercial partner has begun to commercialize fruit and vegetable based edible films. Some of the applications of these films are as replacement for nori in sushi wrappings, ham glaze sheets and pouches for confectionery products, as illustrated in the NewGem Foods website that uses the casting technology developed by WRRC (http://www.newgemfoods.com). The casting technology uses a labcoater with knife over roll coating that allows continuous production of edible films at industrial scale.

Edible films have received increasing interest because films can serve as carriers for various antimicrobials that can extend product shelf life and reduce the risk of pathogen growth. Research done at WRRC show that plant-derived compounds (botanicals, phytochemicals) are useful sources of antimicrobial compounds against foodborne pathogens including *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella enterica*, and *Bacillus cereus* (14-17). Selected compounds were also found to be active in apple juice against *E. coli* O157:H7 and *S. enterica* at concentrations of ~0.01% (18). Burts (19) and Friedman (20) published reviews on the antimicrobial activities of plant essential oils and their constituents against foodborne pathogens.

Fruit-based edible films with antimicrobial plant essential oils were evaluated at WRRC (21-27). Rojas-Graü et al. (21) investigated the effect against *Escherichia coli* O157:H7 of oregano, cinnamon, and lemongrass oils in apple puree film-forming solution (APFFS) and in an edible film made from the apple puree solution (APEF) along with the mechanical and physical properties of the films. Bactericidal activities of APFFS, expressed as BA_{50} values (BA_{50} values are defined as the percentage of antimicrobial that killed 50% of the bacteria under the test conditions) ranged from 0.019% for oregano oil to 0.094% for cinnamon oil. Oregano oil in the apple puree and in the film was highly effective against *E. coli* O157:H7. They found that (a) the order of antimicrobial activities was oregano oil > lemongrass oil > cinnamon oil and (b) addition of the essential oils into film-forming solution decreased water vapor permeability and increased oxygen permeability, but did not significantly alter the tensile properties of the films. Rojas-Graü et al. (22) evaluated the mechanical, barrier and antimicrobial properties of 0.1-0.5% suspensions of oregano oil/carvacrol; cinnamon oil/cinnamaldehyde; and lemongrass oil/citral against the foodborne pathogen *Escherichia coli* O157:H7 in alginate-apple puree edible film (AAPEF). The pres-

Figure 1 - Effect of concentration and type of plant essential oils on bactericidal activity ($1/BA_{50}$) in apple puree emulsion against *Escherichia coli* O157:H7 at 21 C after 1 h exposure.



ence of plant essential oils did not significantly affect water vapor and oxygen permeabilities of the films, but did significantly modify tensile properties. Carvacrol, the main active compound in oregano oil (up to 80%), exhibited the strongest antimicrobial activity against *E. coli* O157:H7. The study showed that the antimicrobial activities were in the following order: carvacrol > oregano oil > citral > lemongrass oil > cinnamaldehyde > cinnamon oil. These results showed that plant-derived essential oils and their constituents can be used to prepare apple-based antimicrobial edible films for various food applications.

Essential oils (EOs) derived from plants are rich sources of volatile terpenoids and phenolic compounds. Such compounds have the potential to inactivate pathogenic bacteria on contact and in the vapor phase. Edible films made from fruits or vegetables containing EOs can be used commercially to protect food against contamination by pathogenic bacteria. These films could extend product shelf life and reduce risk of pathogen growth on food surfaces. Du et al. (26) evaluated physical properties (water vapor permeability, color, tensile properties) and antimicrobial activities against *Escherichia coli* O157:H7, *Salmonella enterica*, and *Listeria monocytogenes* of allspice, cinnamon, and clove bud oils in apple puree film-forming solutions formulated into edible films at 0.5% to 3% (w/w) concentrations. EOs from cinnamon, allspice, and clove bud are compatible with the sensory characteristics of apple-based edible films. Antimicrobial activities were determined by 2 independent methods: overlay of the film on top of the bacteria and vapor phase diffusion of the antimicrobial from the film to the bacteria. The antimicrobial activities against the 3 pathogens were in the following order: cinnamon oil>clove bud oil>allspice oil. The antimicrobial films were more effective against *L. monocytogenes* than against the *S. enterica*. The oils reduced the viscosity of the apple solutions and increased elongation and darkened the colors of the films. They did not affect water vapor permeability. The results showed that apple-based films with allspice, cinnamon, or clove bud oils were active against 3 foodborne pathogens by both direct contact with the bacteria and indirectly by vapors emanating from the films.

Similarly, Du et al. (27) used flavor-compatible allspice, garlic, and oregano essential oils (EOs) in tomato puree film-forming solutions (TPFFS) formulated into edible films at 0.5% to 3% (w/w) concentrations. The results indicated that the antimicrobial activities against the 3 pathogens were in the following order: oregano oil > allspice oil > garlic oil. *Listeria monocytogenes* was less resistant to EO vapors, while *E. coli* O157:H7 was more resistant to EOs as determined by both overlay and vapor-phase diffusion tests. The presence of plant EO antimicrobials reduced the viscosity of TPFFS at the higher shear rates, but did not affect water vapor permeability of films. EOs increased elongation and darkened the color of films. The results of the present study show that the 3 plant-derived EOs can be used to prepare tomato-based antimicrobial edible films with good physical properties for food applications by both direct contact and indirectly by vapors emanating from the films. Also Du et al. (28) evaluated the antimicrobial properties of apple skin polyphenolics incorporated in edible films.

WRRC in collaboration with EMBRAPA from Brazil have been studying the improvement of edible films by incorporation of nanoparticles, nanoemulsion droplets, and nanofibers (30-37). These studies indicated that the increased surface area per weight of smaller film matrix fillers compared to their larger size counterparts are highly beneficial in terms of film mechanical and barrier property improvements. Edible film fillers were prepared by ionic crosslinking (30), microfluidization at high energy shear rates (32), low energy emulsification by catastrophic phase inversion (37), as well as a proprietary FMC process (FMC Biopolymers, Princeton, NJ) for microcrystalline cellulose nanoparticles (29, 31, 33-36).

Coating technology

Research done at WRRC resulted in NatureSeal®, one of the most successful commercial application of coating technology for extending the shelf-life and inhibit discoloration (browning) of fresh-cut fruits and vegetables. NatureSeal® was jointly developed and patented by NatureSeal, Inc., a subsidiary of Mantrose-Haeuser Co., (Westport, Connecticut) and WRRC in Albany, California. NatureSeal® contains a powdered blend of vitamins and minerals. NatureSeal® is proven to maintain the natural taste, texture and color of fresh-cut produce for up to 21 days. The NatureSeal® line of products is allergen-free, sulfite-free and Kosher certified. Several formulations are certified for use on organic produce. One of the most popular applications is on McDonald's Apple Dippers. McDonald sold $54 million pounds of apples in 2005 by using NatureSeal® to coat 50,000 apples a day.

Ultraviolet, infrared and solar technologies

Approximately 40% of Americans are deficient in Vitamin D, an essential nutrient for strong bones, proper liver and kidney function, and a robust immune system. Roberts et al. (38) developed a process to treat whole and sliced mushrooms with ultraviolet light (UV-B) that mimics the sun rays to increase the mushroom content of vitamin D. They studied the effects of high intensity (0.5, 0.75, and 1.0 mW/cm^2), dose (0.5, 1.0, and 1.5 J/cm^2), and postharvest time (1 and 4 days) on the vitamin D_2 formation in Portabella mushrooms (*Agaricus bisporus*) as a result of UV-B exposure, as well as the vitamin D_2 degradation in treated mushrooms during storage. Within each intensity application, dose had the largest effect where more exposure converted more vitamin D_2 from ergosterol. Similar dose across each intensity application resulted in similar vitamin D_2 concentration. Practical commercial production requires as short a treatment time as possible, and intensity was a major factor from this standpoint where the time it took to achieve a similar vitamin D_2 concentration for similar dose exposure was significantly reduced as intensity increased. By using an intensity of 1.0 mW/cm^2 at a dose of 0.5 J/cm^2, the concentration of vitamin D_2 produced was 3.83 μg/g dry solids of mushrooms in 8 min, whereas using an intensity of 0.5 mW/cm^2 at a dose of 0.5 J/cm^2, the concentration of vitamin D_2 produced was 3.75 μg/g dry solids of mushrooms in 18 min. Also, postharvest time did not have a significant effect on vitamin D_2 formation in mushrooms that were treated 1 and 4 days after harvest. Vitamin D_2 degraded in treated mushrooms during storage by apparent first-order kinetics, where the degradation rate constant was 0.025 h^{-1}. The information provided in this study will help mushroom producers develop commercial-scale UV treatment processes to add value to their crop while improving consumer health. By working with the Mushroom Council and Monterey Mushrooms, Inc., WRRC scientists optimized the UV-B light process to assure 100% of the current RDA in vitamin D serving from mushrooms and helped bring it to commercialization.

WRRC is also developing an innovative ultraviolet processing to enhance nutritional value of specialty crops. The effect of ultraviolet-B (UV-B) light as a post harvest treatment to enhance the antioxidant content of carrots and fresh-cut carrot products was evaluated by Avena-Bustillos et al., (39). Whole, baby and various styles of cut carrots were treated at four different UV-B dose levels and the changes in antioxidant capacity, total soluble phenolic content, and phenylalanine ammonia-lyase activity were measured. Both cutting style and dose level were factors for determining carrot responses to UV-B treatment. Antioxidant capacity increased significantly, from 1.4 to 6.6 fold range. Total soluble phenolics results directly correlated with those of antioxidant capacity (R^2 = 0.953) indicating that the enhancements achieved were due to an increase in the phenolic content. HPLC analysis revealed that 5-O-caffeoylquinic acid (5-CQA) was the primary phenolic responsible for this increase. Higher phenylalanine ammonia-lyase activities were also observed in the UV-treated samples indicating that the increase in 5-CQA was a biological response to UV-B exposure. In our study we found that a combination of wounding and UV-B treatment could increase the phenolic content in carrots such that a 100 g serving of UV-B treated sliced carrots could provide over 140 mg total chlorogenic acid equivalents. Thus UV-B treated fresh-cut carrots could provide an inexpensive source of phenolic antioxidants to regular diets.

Considering that the foods with the highest antioxidant capacities are often the most expensive and typically only seasonally available, the potential to enhance the antioxidant capacity of carrots, a widely cultivated and relatively inexpensive crop, through a combination of wounding and UV-B treatments offers an exciting opportunity to increase consumer accessibility to dietary choices that are rich in antioxidants. Ultraviolet B treatment results in more than doubling of total soluble phenolics and antioxidant content in baby carrots. Increasing UV-B exposed area increases antioxidant capacity of fresh-cut carrots. Commercial carrot products shaped as baby carrots, sticks, coins and chips with increased area/weight ratio, showed a linear increase in antioxidant capacity when exposed to UV-B light at doses of 130 mJ/cm^2 on two sides. However, before this process can be taken to a commercial scale, more studies are needed to determine the influences of variety, harvest season, and storage on the effectiveness of the treatment, as well as studies that address the consumer acceptance of the enhanced carrots and carrot products.

The California food processing sector is the largest in the United States and also the third largest energy and water user in California, 80% of which is from the fruit and vegetable industry. Over 70% of the energy used by the fruit and vegetable industry comes from heating operations (blanching, drying, pasteurization, etc.). The development and scale-up of new infrared food processing technologies can improve the energy, water and processing efficiency in the food industry. WRRC designed a mobile infrared demonstration unit for blanching and dehydration to be shipped to food companies for testing and evaluation of water and energy savings and increased quality and added-value products. The current development of infrared peeling for tomatoes using catalytic infrared emitters at WRRC aims at replacing the currently used commercial lye and steam tomato peeling methods and eliminating water and chemical usage in the process, which should generate significant environmental benefits. Improved product quality, reduced peeling loss with similar or slightly firmer texture and similar or slightly longer heating time is expected with this novel infrared peeling technology. Infrared radiation is an emerging method that may be also used to replace hot air and steam in drying and blanching of fruits and vegetables. Compared with hot air drying, IR heating offers many advantages, such as greater energy efficiency, heat transfer rate, and heat flux, which result in higher drying rate and reduced drying time (40).

The traditional method for designing solar drying of foods involves time-consuming prototyping of cabinet and solar collector and a static approach ("drop it in the box and let it dry"). Our solar drying research of specialty crops involves a modeling approach with test designs using multiphysics modeling software, dynamic feedback control of dryer configuration based on real-time measurements of temperature, humidity, insulation, etc.

Innovation at WRRC is the key for processing agricultural products with enhanced nutritional value, improved safety and sustainability of agricultural and food processing operations benefiting both domestic and international consumers.

"Never before in history
has innovation offered promise of
so much to so many in so short a time."
Bill Gates. Microsoft

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