The Effect of Chlorine Dioxide on Sliced Tomatoes used in Retail and Foodservice

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THE EFFECT OF CHLORINE DIOXIDE ON SLICED Tomatoes
USED IN RETAIL AND FOODSERVICE

A THESIS
PRESENTED TO
THE GRADUATE SCHOOL OF
CLEMSON UNIVERSITY

IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE
MASTER OF SCIENCE
PACKAGING SCIENCE

BY
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MAY 2024

ACCEPTED BY:
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ABSTRACT

As food prices continue to rise, many consumers are looking at ways to cut back on spending and many look to how much they spend on food. Food waste in an average American household of four leads to about $1,500 worth of unused/wasted food annually,

This study was conducted to see how the use of Chlorine Dioxide (ClO₂) could be used to treat and extend the shelf life of freshly sliced tomatoes for food service applications. Prior research in this regard has looked at whole tomatoes as opposed to sliced varieties, and many have not utilized a sensory panel to comment on a consumer’s perspective of how the treatments could affect their decision making. Through the use of texture analysis, color readings, as well as sensory were used with statistical analysis performed to determine if any showed significance based on the treatment that was performed on the tomatoes, with treatments ranging from control (no ClO₂ treatment), bulk treated by ClO₂, and finally bulk treated by ClO₂ with a slow-release media sachet in package during storage. It was found that there was no significance with regards to treatment when it came to textural analysis by either TPA or shear blade tests throughout the refrigerated storage period of 20 days. There was a significant difference related to sensory testing. Panelists significantly preferred sliced tomatoes
treated in bulk and then stored with in-tray slow-release sachets compared to tomatoes treated in bulk only or the control (untreated) tomatoes. There were no significant differences for tomatoes based on sensory assessment of color, aroma, or taste, indicating chlorine dioxide treatment had no negative effects on the sensory properties of the fresh sliced tomatoes. This is important because the tomatoes can be treated with a quality shelf life extending step while still maintaining sensory acceptability. The results of this study can be used to help determine if use of chlorine dioxide for shelf-life extension of fresh sliced tomatoes is beneficial for use with foodservice operations.
Dedication

I would like to dedicate this to my Poppop, Raymond Rauenzahn. A phenomenal teacher, coach, and great inspiration to strive further and to always work to improve yourself. This is for you.
ACKNOWLEDGMENTS

First, I would like to thank my committee for their patience and understanding and their wisdom in guiding me. You helped me grow to become a better scientist and researcher.

Secondly, I would like to thank my two undergraduate students that were assisting me through the duration of this study. Liam and Seth, you are phenomenal scientists, you did more for me than I could have imagined.

Finally, I would like to thank my family and friends, for their understanding and unconditional support that helped me through all the tough times and long nights.
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CHAPTER ONE
INTRODUCTION

Food waste in America is climbing higher and higher every year and while many talk about buying less from the store or going for smaller portions, it doesn’t appear that food waste is decreasing. Fighting food loss in a developed nation can look to making adjustments at distribution and retail levels where a study found that 37% of food loss occurs at the retail and consumption stage of food and globally comes out to be about 931 million tons of food wasted per annum (Buss, 2022). Food packaging should be viewed as a way to solve this problem with shelf-life extension of fresh produce being an ongoing topic of research and development for academia, industry and regulatory agencies.

Active packaging, commonly referred as “smart” packaging, is packaging intended to sense internal/external changes to environments and adjust its own properties as well as its effect on the internal package (Brody, Strupinsky, & Kline, 2001). Active packaging involves the shelf-life extension of the food product by the inclusion of antimicrobial compounds designed to inhibit/delay microbial growth is a growing innovative field for extending the shelf life of fresh food and one such active packaging method is antimicrobial
packaging. Antimicrobial packaging has multiple delivery systems such as coatings, embedded film and sachets.

Chlorine dioxide has been used to treat fresh produce as a one-time treatment prior to packaging using a generator. Other methods that have been examined include films encapsulated with chlorine dioxide release (southwest institute material) and sachets that contain dry ingredients that become active upon exposure to humidity in the packaging headspace and by the food itself.

Tomato production value for the fresh market in the United States was valued at $715.63 million USD in 2023 (M. Shahbandeh, 2024). Tomatoes also are full of nutrients with many varying health benefits such as lowering risk of heart disease, cancers, as well as increasing the body’s immune system (What are the health benefits of tomatoes? 2023). According to the Environmental Protection Agency (EPA) it is estimated that over $2.3 Billion USD of tomatoes are wasted per annum by U.S. households noting that it is just a drop in the bucket for total food waste in the US which is estimated to be closer to $166 Billion USD per annum (What's up with all the wasted food? 2016). The difference in valuation here is to taken with the understanding that the initial valuation shows total production value in the US while the second valuation is waste which would include any and all tomato products that are also imported to the US which is not accounted for in the initial production valuation. A possible solution to the problem of food
waste and how it can be tackled is turning to how we package our produce and store it. Active packaging is a tool in our arsenal that should be further looked at to assist in this fight against food waste.

In this study the goal was to look at how active packaging can play a role in reducing food waste by providing an extension of shelf life for tomatoes through using Chlorine Dioxide treatments.
CHAPTER TWO
LITERATURE REVIEW

Tomato Production, Handling, and Shipping

Tomatoes are the second most consumed vegetable in the US behind potatoes (Kantor & Blazejczyk, 2020). They are full of vital nutrients and are known to help against many common health maladies such as heart disease and kidney stones (Tomatoes.2021; Swartzendruber, 2018). There are many differing varietals of tomato however most foodservice operations source tomatoes from only a few main varietals such as Beefsteak, also known as Round tomatoes, Roma, Cherry, and Grape tomatoes (US Foods, ). It is estimated that the production value of tomatoes headed for the fresh market, not processed (i.e. tomato paste, tomato puree), was around $615.88 million USD in 2022 (Shahbandah, 2023). Tomatoes are grown at commercial scale in about 20 states with Florida now the top producer of tomatoes over California due to ongoing droughts disrupting the normal growing conditions (Tomatoes.2021).

Outside of the issues of climate induced loss of product there is the traditional food loss and waste occurring across all levels of the production chain. It is estimated that about half of total fruit and vegetable loss occurs
in the farm to pre-retail supply chain and that they account for about a third of total U.S. food loss at the retail and consumer level by weight (Minor et al., 2020). While the data presented shows that the highest levels of loss are occurring in the farm to pre-retail supply chain this study is more focused on how efforts can be made to cut down on the level of waste occurring at the retail and consumer level and is believed that if this level of waste can be brought down it’s a starting point to lowering waste in other areas of the supply chain.

Tomatoes are being looked at specifically as the focal point of the project partly because they are a high-volume product for foodservice with a relatively short shelf life. As of 2021 tomatoes are the second most consumed vegetable in the U.S. behind that of the potato with a fresh market and processed consumption of 20.3 pounds and 73.3 pounds per capita respectively (Tomatoes.2021). In 2020 it is estimated that 12,619.2 tons of fresh market tomatoes and 11,312,256 tons of processing tomatoes were harvested from 272,900 acres having a total valuation of approximately $1 billion. Due to the high nutritional yield of tomatoes, based on being a good source of Vitamin C, Vitamin A, as well as antioxidants, it is no surprise to see the demand for tomatoes grow to meet the diverse dietary needs of people (Tomato market size & share analysis - growth trends & forecasts (2023 - 2028) 2023). Tomatoes when stored at refrigeration temperatures below 41 F will have approximately two weeks of shelf life,
while if stored on a countertop in room temperature conditions it will
deteriorate much faster and last up to one week instead (Beefsteak tomato.).

Depending on the distance that tomatoes travel to market they can be
harvested either when they’re green, meaning they’re fully grown and will
ripen by the time they get to markets further away. If the tomatoes are
bound for closer more local markets, they would be picked closer to a
turning stage where the tomato is pink. Tomatoes ripen through a self-
regulated internal gas called ethylene, this is the chemical that allows the
tomato to turn from the green it starts as to the deep bodied red that many
consumers are used to seeing (Hoppenstedt & Patton, 2022). Tomatoes
undergo significant changes to their sugar, organic acids, lycopene and other
compounds and phytochemicals as they progress from the green stage to
the breaker stage of ripening (Choi & Park, 2023).

Tomatoes are picked by hand and placed into plastic buckets that hold
between 40-50 pounds of product. These are then brought to a field truck
where they are emptied out to a pallet bin or a gondola where pallet bins
hold 800-1200 pounds of produce and gondolas hold between 16,000-
24,000 pounds of fruit. Once the field truck is filled it is transported to the
packinghouse where the tomatoes are transferred to the packing line. The
tomatoes are washed, pre-sized, waxed, sorted and graded, sized, packed
into shipping containers, and unitized for shipment (Sargent, 1998).
According to the United States Department of Agriculture (USDA), there are two sets of standards and grading for fresh tomatoes depending on whether the tomatoes are field, or greenhouse grown. According to material from the USDA Agricultural Marketing Service’s Fruit and Vegetable Division, field grown tomatoes can be graded in one of four ways as indicated by §51.1855 – 51.1858 (APPENDIX I) (United states standards for grades of fresh tomatoes1997). The standards cover the four grades a fresh tomato could be listed as such as U.S. No. 1, U.S. Combination, U.S. No. 2, and U.S. No. 3. All of these are based around a few key identifiers such as size, coloration, and whether they are reasonably well formed and free of deformities. Tomatoes can vary in color from reds to yellows and oranges to more purple tones and have varied shapes ranging from oval shaped to elongated pear-like shapes and usually contain cells of small seeds surrounded by a jelly-like pulp substance (Tomato.2023). As pictured in Figure 1, it can be seen how a tomato is sectioned out into different sections, with the outer skin being the outer pericarp made up of the Exocarp, or skin of the tomato, Mesocarp, and Endocarp. The jelly-like substance surrounding the seeds is the locular gel, and the core of the tomato is referred to as the columella.
The tomato fruit's susceptibility to chilling injuries leaves it with a narrow range for storage conditions. The optimum conditions for tomato ripening in packing houses are 68°F and 85-95% relative humidity and exposure up to 150 ppm (Sargent, 1998). Exposure to temperatures above 85°F lead to the development of less red pigmentation and instead more orange pigmentation. If delayed ripening is preferred, then tomatoes should be stored below 68°F but no lower than 55°F as chilling injuries may occur at the lower temperature and the fruits never ripen to their full color and flavor (Guan, 2017).
Whole tomato shelf life is about 2 weeks at refrigerated temperatures, however once cut the shelf life of them decreases to a few days (Beefsteak tomato.). Because tomatoes are usually consumed at their peak full red color stage, this indicates color is the most important external characteristic in assessing ripeness, postharvest life, and a major factor towards a consumer’s purchasing decision (López Camelo & Gómez, 2004).

There are many varietal types of tomato that are commonly consumed with one of them being the Beefsteak tomato. The most common form that Beefsteak tomatoes and its subvarieties are consumed is sliced, from a simple sandwich made at home to a sub shop’s topping bar to fresh caprese, fresh sliced tomatoes are common uses for these varietals.

The consumer perception of tomatoes is important and drives whether or not a person would choose to consume one. From the way the tomato looks on the shelf (color, bruises, scarring, etc.) to how it feels when they grip the fruit (firm, soft, mushy, etc.), these all impact the consumer. However, it is hard to be able to scientifically relate these more ambiguous personal points to a more concrete mechanical point of data, which is why they are going to be combined. By combining both the subjective results (sensory) with the quantitative results (texture analysis) there should be a good positive correlation between the two results. Consumers preference for tomatoes are varied, according to a study, with a participant count of 1037, completed by Oltman, Jervis, and Drake (Oltman, Jervis, & Drake, 2014) the
most important attribute for fresh tomatoes was color, with red being the most preferred color, with firmness of tomato and juice when sliced were right behind in level of importance. They go on to discuss that consumers prefer a red coloration but that also high in acceptability is a dark red coloration before falling off with light red, orange, yellow, then green.
**Fresh Tomato Color Measurement**

Color determination is completed via non-destructive means based on visual or physical measurements. The methods are based on evaluation of either light reflected from the surface of a product or transmitted through it. Simple color charts and dictionaries routinely are used in field, packinghouse, fresh-cut processor facilities or even retail stores (Barrett, Diane M., Beaulieu, & Shewfelt, 2010).

Analytical sensory methods of evaluating color are faster and easier in many ways than instrumental methods and they also have the advantage of requiring no specialized equipment and may be standardized through use of color charts. The disadvantages, however, are that such methods may vary considerably due to human differences in perception and human error (Mitcham, Cantwell, & Kader, 1996). Perception of color is entirely determined by the human eye and relies on the photoreceptors in them, and if certain cones aren’t functional then it becomes harder to correctly determine coloration and hue (Sipos, Nyitrai, Szabó, Urbin, & Nagy, 2021).

Instrumental methods are less variable and can be used to measure small differences, however disadvantages do exist and it’s that many of these instruments are expensive. Tristimulus colorimeters simulate the human eye by replacing receptors with filters on each primary hue (Barrett, Diane M., Beaulieu, & Shewfelt, 2010). Colorimeters give measurements that
can be correlated to human eye brain perception and give tristimulus (L*, a*, and b*) values directly (Phillips, 2023).

Color space may be divided into a three-dimensional (L, a, and b) rectangular area with L* (lightness) axis going vertically from 0 (perfect black) to 100 (perfect white) in reflectance or perfect clear transmission. The a* axis (red to green) considers the positive values as red and negative values as green with 0 being neutral. The b* axis (blue to yellow) expresses positive values as yellow and negative values as blue where 0 is neutral, all of these are viewable in a 3D spatial diagram as seen in Figure 2 below.

With fruits the a*/b* ratio is useful as for green fruits the ratio can be expected as negative, approximately 0 for yellow fruits, and a positive ratio for orange to red fruits. In a study performed by Ali Batu (Batu, 2004), they found that the USDA color stages related to an a*/b* ratio with increasing values as the USDA color stages increased with time. They found that the light red stage, common for many market tomatoes, had an a*/b* range of 0.60 to 0.95. The red stage was noted to be more overripe and showed a range of 0.95 to 1.21 using an a*/b* ratio.
The pigment responsible for the coloration of what most consumers see as the standard deep red of the tomato is caused by the varying levels of lycopene in the tomato and is mainly known to consumers as being a good antioxidant found commonly in tomatoes (Shi, 2008).

Figure 2 - CIELAB Color Scale - Ly et al., 2020
Saad, Ibrahim, & El-Bialee (2016) found that chromaticity, which specifies both the hue as well as the saturation level (Bouman, 2024), values and internal quality parameters changed during ripening and that the $L^*$, $b^*$, $h^\circ$, and $\Delta E$ all had tendencies to decline as the fruits continued to ripen. The $h^\circ$, or hue angle, is the color's position around a color wheel and is often measured in the counterclockwise direction from the red-related cardinal axis ($Hue \ angle (H)$; Clayton, 2017). The $\Delta E$ is also known as the total color difference, which can be calculated and determined based on the $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ differences, with a representation of a line between a sample and the standard (Gordon, 2022). They also found that the opposite tendency was determined with $a^*$, $a^*/b^*$ ratio, TSS and lycopene content and that the chromaticity values showed to have an important impact in internal quality parameters, those being the TSS and lycopene content. TSS is simply the amount of soluble solids that are in liquid, the value of such can affect the taste of fruits as it can indicate the total sugar content as well as a portion of soluble proteins (Kusumiyati, Hadiwijaya, Putri, Mubarok, & Hamdani, Feb 1, 2020). They also concluded there was good correlation between chromaticity values that were gathered by both image and colorimeter and that they could estimate lycopene content during tomato maturity stage by both methods.
Texture Analysis of Fresh Tomatoes

Texture profile analysis (TPA) as well shear blade tests are two of the most common tests (LANA, MILZA M., TIJKENS, DE THEIJJE, DEKKER, & BARRETT, 2007). With the shear blade test imitating what would be akin to biting through a portion of a slice of tomato like one would do when biting into a sandwich while the texture profile analysis, using a flat compression plate, does well to mimic what mastication would be. Both of these tests give a picture of how the tomato changes over time but lack the ability to tie into a consumer’s more complex views of what makes tomatoes acceptable.

According to Jackman et al. (Jackman, Marangoni, & Stanley, 19990) for measuring the firmness of chilled injured fruits evaluated the use of both a flat plate compression and flat tipped puncture probes, with a recommendation to use puncture tests rather than flat plate compression. This is because the tomatoes are kept at chill injury-inducing temperatures and a puncture test would seem most suitable for firmness measuring. Barrett et al. (Barrett, D.M. (Quest International, Silverton, OR.), Garcia, & Wayne, 1998) carried out puncture tests on tissue disks, one obtained from the equatorial region of tomato pericarp and another being a single 6.35 mm thick slice taken from tomato fruit at the equator. Pericarp tissue disks evaluated skin side down using a 5mm probe, for slice evaluation a 2.5 mm diameter flat tipped cylindrical probe with a 50kg load cell were used for the measurement of outer pericarp, radial arm and columella tissues at the cut
surface. These authors found that puncture tests carried out on pericarp disks correlated well with flat plate compression tests on the whole fruit.

Tomatoes, like other soft skinned produce, suffer from high chances of microbial decay especially when the outer layer of skin is damaged. Tomatoes can suffer from a mix of bacterial pathogens such as *Pseudomonas, Erwinia, Xanthomonas, Bacillus*, as well as lactic acid bacteria (Barth, Hankinson, Zhuang, & Breidt, 2009). The FDA (*Program information manual: Retail food protection storage and handling of tomatoes*. 2022) released a study showing the growth kinetics of *Salmonella Enteritidis* and *Salmonella Newport* in Beefsteak at room temperature (72°F) and refrigerated temperature (41°F). It showed that cut beefsteaks held at refrigerated temperatures showed no exponential growth rates and they had an indefinite lag phase duration. Where as the samples left at room temperature saw an exponential growth rate of 0.22 log/h to 0.30 log/h and had a range of 5.29 hours to 7.49 hours for lag phase duration.
Active Packaging and Chlorine Dioxide

Active packaging is a technology that is being looked at as a way to have the package do more for the food in both food quality and safety aspect. Active packaging can work by either absorbing food based chemical compounds, such as ethylene, or by releasing an active agent into the package surroundings (Guo, Zhang, & Jin, 2024). By controlling the product inside by either absorbing what it puts out or by releasing agents to control the inner atmosphere, it can allow for produce to have a longer shelf life and makes it easier for distribution (Active packaging: Extending the shelf life of fruit and vegetables. 2021). As consumers turn to more health-conscious choices there has been a more noticeable shift to buying more fresh produce whether it is for home consumption or for a quick meal on the go. However, there is an abundance of produce that goes to waste before consumption (Minor et al., 2020). To combat this, suitable post-harvest technologies are being developed and looked at that can employ an effective method to disinfect and preserve fresh produce without affecting sensorial qualities and importantly nutritional quality (Singh, Maji, Lee, & Gaikwad, 2021). Because produce is quickly contaminated in post-harvest due to microorganisms, damage, or human contamination from transportation and processing a food-friendly antimicrobial compound is required to best ensure the food safety and quality of the product (Singh, Gaikwad, Lee, & Lee, 2017)

Sodium hypochlorite is the most used sanitizer by the food industry due to its low cost and ease of use (Chemical disinfectants.2008; Ran, Qingmin, & Maorun, 2019). Per the CDC, the exact method for which chlorine destroys microorganisms isn’t known and inactivation of microorganisms by chlorine can occur a number of ways such as oxidization of certain amino acids and enzymes as well as ring chlorination of amino acids (Chemical disinfectants.2008). In industry chlorine can be used as a food contact sanitizer up to a solution of 200 part per million (ppm) and left on equipment or other food contact surfaces no longer than 30 minutes before corrosion starts to occur (Use of chlorine in the food industry.). In wash water for produce chlorine is suggested at a range of 50 to 200 mg/L (ppm), a pH of less than 8.0, and a contact time of between 1 to 2 minutes for optimal safe sanitization (Northcutt, 2021). As stated before chlorine is relatively cheap and is also easy to get and use, however some disadvantages are that the efficacy of its disinfectant capabilities relies on a controlled pH, as at higher pH’s it will start to gas-off (Northcutt, 2021). It also is highly corrosive, can mix with ammonia to create deadly chlorine gas, as well as possibility to create carcinogenic by-products (Chemical disinfectants.2008).

Chlorine dioxide (ClO₂) was first discovered by Sir Humphry Davy in 1814, however it was not commercially produced until 1940 where it was used as a bleaching agent for textiles, wood pulp, paper, and also flour (Gray, 2014). Chlorine dioxide use peaked in Europe between 1975-1980 due
to a number of advantages that were found: 1) higher detection threshold by comparison to bleach, 2) when compared to chlorine a decrease in organoleptic hindrance was noted, 3) compared to bleach there was less chlorinated by-products being formed, 4) oxidation of iron, manganese, as well as sulfides enhanced clarification, 5) effective over a wide pH range, and 6) compared to ozone or chlorine, chlorine dioxide was found to be more effective against viruses (Kessler, 2020). Liquid chlorine dioxide use was approved by the U.S. EPA in 1967 as a disinfectant, however the gaseous form was not approved for use until 1988 (Gottilla, 2014). Chlorine Dioxide was approved by the Food and Drug Administration for post-harvest use in agricultural produce and listed as generally recognized as safe (GRAS) since 2006.

The regulation of chlorine dioxide has since been regulated and codified as part of the Code of Federal Regulations under Title 21 (21CFR173). Section 173 specifically discusses the usage of chlorine dioxide as a secondary direct food additive that has been permitted in food for human consumption and can be found under appendix II below.

Aqueous chlorine dioxide sanitizers are used in a wide variety of commercial applications, however the issues with these types of sanitizers over gaseous forms is that with high plant mass being washed all at once, there is a greater risk of cross-contamination especially if the wash water is recycled. By comparison, gaseous treatments use little if any water and are
more capable of treating areas and irregularities on produce surfaces that aqueous sanitizers have more difficulty in reaching (Bridges, Rane, & Wu, 2018).

Chlorine dioxide when gaseous is not stable, therefore it is commonly generated when needed by reacting sodium chlorite (NaClO₂) with chlorine gas or acids. There are two methods for generating chlorine dioxide gas; one uses commercially available dry media (NaClO₂ and FeCl₃) and the other uses NaClO₂ and HCl (Chai, Hwang, Huang, Wu, & Sheen, 2020a). Chlorine Dioxide gas has been found effective in inhibition of both foodborne as well as spoilage microorganisms for a wide variety of produce (Gómez-López, Vicente M., Rajkovic, Ragaert, Smigic, & Devlieghere, 2009; Linton, 2005; Yam, 2018). It has been reported by Bridges, Rane, and Wu (2018) that an application of ClO₂ gas of 300 mg ClO₂ to 2.0Kg of beefsteak tomatoes resulted in >7.0 log CFU/g reductions of *Escherichia coli* (STEC), *Salmonella*, and *L. monocytogenes*.

For food packaging applications the four common methods of delivery for gaseous ClO₂ for active antimicrobial systems are sachets, a coating of the active material to the inner food contact surface of the package, incorporating the active materials into the structural property of the package, or by adding the active component into the headspace (Singh, Maji, Lee, & Gaikwad, 2021). Sachet technology can be considered as the simplest method to deliver the gas and is commonly done with dry media precursors.
A downside for sachets is that consumers occasionally will misconstrue them to be a part of the product they have bought and might mistakenly consume them. Sachets also struggle with products that have high moisture or are liquid products. Including dry media into polymeric film is still rather novel and has only really been incorporated into biomedical applications (Singh, Maji, Lee, & Gaikwad, 2021). Encapsulation methods are relatively novel but has gained acceptance in pharmaceutical, cosmetic, as well as food sectors and is when the active material is captured in a shell material where it creates encapsulated particles on the nanometer, micrometer, or millimeter scaling (Zanetti et al., 2018). The final method is through a self-releasing label which have a controlled release inside the package to help preserve the quality of food products while also increasing the microbial safety (Smith, Ernst, & Herges, 2015). It works on a system where the label integrates with a chemical reaction which activates via a controlled activation mechanism (Saade et al., 2018).
The delivery method for this study will be via simple sachet and both the sachets and the media being used in this study was obtained from ICA TriNova Co. (Atlanta, GA) and consists of two parts, part A (NaClO₂) and part B (FeCl₃). Chlorine dioxide gas is generated by mixing an equal amount of parts A and B together in a sachet, with the reaction equation being:

\[ 3\text{NaClO}_2 + 3\text{H}_2\text{O} + \text{FeCl}_3 \rightarrow 3\text{ClO}_2 + \text{Fe(OH)}_3 \]

Chlorine dioxide is affected by several factors as to its efficiency with such factors affecting it the most being amount of gas released, contact time with the food, relative humidity, and also storage temperature. Knowing that chlorine dioxide is a water-based reaction it is understandable that relative humidity plays a role in how effective the chemical is in its performance, however it should be noted that the factor of most effectiveness is the amount of gas released. The antimicrobial capacity depends on changes in temperature and was found that the inactivation rate of chlorine dioxide increased with an increase in the experimental temperature (Singh, Maji, Lee, & Gaikwad, 2021).
While increasing the level of chlorine dioxide leads to a greater inactivation of microorganisms, when applying to produce there is the downside of causing unwanted sensorial effects such as phytotoxicity which could lead to browning of the outer skin layer as well as possible off odors if too much gaseous chlorine dioxide is used.

Compared to a control sample, a lower weight loss and lower firmness value was noticed in tomatoes packaged with ClO2 gas. Wrinkling was also observed in the skin of tomatoes which is associated with weight loss when treated with 10 mg/L gaseous ClO2 for 3 minutes. In general, ClO2 has a lower efficiency against Gram-positive bacteria compared to gram-negative bacteria, whereas it has intermediate tolerance for molds and yeast fungus (Singh, Maji, Lee, & Gaikwad, 2021).
Sensory Analysis of Tomatoes

Sensory analysis is the process of examining the properties of a product or food through the use of the five basic senses (touch, taste, sight, smell, and hearing) from panelists (Ruiz-Capillas & Herrero, 2021). There are two main types of sensory tests that can be conducted, those being qualitative and quantitative descriptor tests (Marques, Correia, Dinis, & Vilela, 2022). Sensory tests are conducted with panels to complete the various tests, with panels being either an untrained panel, usually consisting of a couple hundred participants commonly also referred to as a consumer panel, or a trained panel, which is usually composed of a small number of panelists, usually less than 10 panelists, that have been trained specifically on what the panel is looking into. A third type of panel exists called a semi-trained, or frequent panel, in which people more familiar with the product or products being tested are brought in frequently over a period and usually consist of 20-30 members.

Sensory properties of tomatoes were characterized by a study performed by Stone and Sidel via Quantitative Descriptive Analysis (QDA) using a trained panel of 10 judges (Krumbein, Peters, & Brückner, 2004). The “Vanessa” varietal tested in this study was a long-life tomato, which is a round tomato, characterized with intensive, tomato-like, and sour notes
Other studies of tomatoes performed looked at different qualities of the produce. A study performed by Oluk et al. (OLUK et al., 2019) looked at how panelists evaluated the produce with red lighting being used, which minimized the effect of color on the panel. This is a common technique when color is not a source of interest to the study and instead allows the panelists to focus more on the other aspects of the produce such as flavor, texture, or smell. Another study performed by Stommel et al. (Stommel, Abbott, Saftner, & Camp, 2005) also used red-masked lighting of tomatoes for the panelists however after an initial test round under the masked lighting they took the red shade away and had the panel repeat the same set of questions now under standard white lighting conditions. This would allow for a better understanding of how color really plays into the consumers’ perception of produce and how it is relied on to determine the quality of a product.

Sensory analysis plays a role in determining shelf life of products as this is how a consumer perceives the product. Shelf life is the determined “life” of the food or product before it has lost its quality or safety attributes based on given characteristics or known conditions (Carrasco, Valero, & Ma García-Gimeno, 2012). If the consumer fails to find the product of a deterministic quality that meets their approval, then it does not matter if the product can last long if it smells horribly or appears unseemly for what the produce should be. A study completed by Vignesh and Bindu (Vignesh & Nair,
2019) looked at how an edible coating for tomatoes could extend the shelf life of the produce, using metrics such as weight loss, pH, appearance changes, as well as sensorial analysis to determine if the produce was sufficiently viable for consumers as well as if this novel method could produce the intended effect of extending the life of tomatoes. Their study had panelists perform a preference test as well as a 9-point hedonic scale of acceptability to determine how the produce faired. This is also mirrored in a separate study performed by Wabali, Esiri, and Zitte (Wabali, Esiri, & Zitte, 2017) in which they were looking at the usage of potassium permanganate to extend the shelf life of tomatoes while also ensuring that they maintain a level of consumer acceptance.
1. Introduction

Fresh foods are susceptible to many forms of contamination leading to food loss and food waste. The United States discards nearly 60 million tons every year (Food waste in america 2024.) and is estimated to be almost 40% of the US food supply, with the approximate value of this waste at nearly $218 billion. It is through this lens that this study looks to minimize food waste.

Tomatoes are the second most bought and consumed produce, just behind potatoes. Tomatoes are consumed in many different forms including in some sliced form. Intact tomatoes stored at room temperature have a shelf life of approximately 2 weeks (Fry, 2023) however slicing decreases that to just a few days (Balas, 2023).

Chlorine Dioxide (ClO₂) is an oxidative agent with a broad antimicrobial spectrum. It was found that it is just as effective and reliable as Chlorine, which is commonly used in the agri-food industry but has drawbacks due to the highly corrosive nature of chemical as well as the ability to generate toxic compounds. Aqueous ClO₂ sanitizers are used in a wide variety...
however in a high mass plant wash, there is ample ability for cross contamination. The advantage of gaseous treatments is their limited use of water and higher diffusion coefficients which in turn can result in better outcomes in treating produce with irregularities than their aqueous counterparts.

There are many varieties of tomato that are used by consumers and industry, and a common varietal that is used across the spectrum is the beefsteak tomato. The beefsteak tomato was cultivated to be the tomato best served sliced and is commonly found on many common food items such as burgers and sub sandwiches.

The aim of this study was to develop a method of shelf-life extension for freshly sliced beefsteak tomatoes based on gaseous chlorine dioxide. The treatment could be included in a slow-release container-style active packaging that would extend the viability of consumption of the fruit without degrading the sensorial qualities.
2. Materials and Methods

2.1 Chemicals and reagents

Chlorine dioxide precursor and acid reactant was provided with sachets from ICA-TriNova (Newnan, Georgia, USA). Fresh beefsteak tomatoes were purchased from Publix, Clemson, SC. Five-gallon containers for bulk-treatment of tomatoes were obtained from a local store. Five-inch fans were obtained from Amazon.com. Phosphate buffer (PBS) was prepared in the laboratory (per liter NaCl 8g + KCl 0.2g + Na₂HPO₄ 1.44g + KH₂PO₄ 0.24g, pH of 7.2). Swabbing of sliced tomatoes performed with Hygiena Q-Swab™ containing 1 mL of sterile Letheen Broth. Enumeration of the total aerobic plate count and yeasts and molds was performed on 3M Petrifilms. All chemical reagents were purchased from VWR. Chlorine dioxide was prepared by combining equal amounts of both precursor reagents provided by ICA-TriNova, based on the amount of tomato that was going to be treated with the amount of combined precursor being 2g precursor per 1Kg of produce being tested. This would then be added to a sachet that was given to be used in the study. For the extended-release sachets used, the Part A precursor of NaClO₂ was used with 2g added into the sachets for the Sterilite
12 Qt storage containers selected for in-storage sachet usage per the directions from ICA-Trinova.

### 2.2 Determination of chlorine dioxide concentration

In the initial hour time of bulk treating, the tomatoes were exposed to a concentration of 11 parts per million (ppm) of ClO₂. This is based off the reaction information given that 5.5 mg ClO₂ per gram of precursor supplied. Amount of dry precursor used was based on the amount of tomatoes that were to be tested with a ratio of 2g precursor to 1Kg of produce being tested, i.e. 10.0g media (5g part A + 5g part B) generated 55mg of ClO₂ for 10Kg of produce. This was released over a one-hour period of time during the initial bulk treatment of the produce. During the course of the study the treatment group that underwent further extended release of chlorine dioxide through in-package slow release was done at a rate of 0.01mg/g per day. These extended-release sachets were comprised of just Part A of the dry media combination that was used in the initial bulk treatment phase, and maintained at 2g of Part A per container, per directions given by the supplier.
Following the information presented in the study completed by Samuel Kessler (Kessler, 2020) an indicator test was set up using potatoes cut into strips and soaked in 0.5 M KI for 30 seconds. Initial L readings (Lo) were obtained using a Minolta Colorimeter CR400. Strips of potato were placed into the treatment buckets at representative intervals of the layers of tomatoes and taped to be held in place. Once secured the potato strips underwent treatment to determine if appropriate airflow was present in the bucket. After treatment L values (Lr) were obtained. An average was made for the layers and color change was expressed as ΔL = Lo - Lr.
Figure 4 - Potato slices positioned in bucket
Figure 5 - Post-treatment potato slices positioned in bucket
Figure 6 - Post-treatment potato slices positioned on bucket lid
Figure 7 - Post-treatment potato slices
2.3 Tomato Treatment and sliced sample preparation

Tomatoes were brought directly from the local supermarket, where they came directly off a fresh shipment truck, to the laboratory and were maintained at room temperature. Five-gallon containers were weighed and zeroed out and then beefsteak tomatoes were added to the buckets using latex gloves until they stacked up to 3 layers to a total of 18 tomatoes. The total weights of the tomatoes per container were recorded. Using the recorded weight of the tomato in the five gallon bucket an appropriate amount of precursor was added to a sachet as described in section 2.2. A battery operated five-inch fan was affixed to the lid of the bucket using tape to help with gas distribution. The sachet generating the chlorine dioxide was taped just below where the lid was connected to the container and above the tomatoes enough to not cause overexposure to the sample. The fan was turned on to its fastest setting and then the lid was carefully closed and sealed with the fan running and the taped sachet inside. The containers were kept at room temperature for one hour following manufacturer’s instructions (ICA TriNova). After the hour period, the containers were opened and the sachets were removed. Control (not treated) and chlorine dioxide treated samples were sliced immediately after treatment with ¼” push through slicer. Each sliced
tomato was kept assembled as a “whole” and then were placed into Tupperware containers as described below.

2.4 Tomato Storage

Sterilite 12 Qt storage containers with dimensions of 16 7/8” L x 11 ½” W x 5 7/8” H, were weighed empty first, without the snap fit lid, then had 6 sliced beefsteak tomatoes added to each container. Gloves were worn to ensure sterile handling during transfer of tomatoes. Tomatoes were filled into the storage containers by sequentially removing one tomato at a time from the treatment containers. The storage containers were packaged with the following treatments: (1) control storage containing tomatoes with no treatment, (2) chlorine-dioxide treated tomatoes and (3) chlorine-dioxide treated tomatoes that had an additional in-package chlorine dioxide sachet placed in the storage container. The storage containers were then placed in a refrigerator at refrigeration conditions of 5°C for 20 days and analyzed at selected time intervals. The in-package sachet storage containers were placed into a separate refrigerator unit to prevent any accidental or possible treatment contamination from the active sachet.
2.5 Tomato swabbing and microbial and yeast and mold enumeration

Swabbing for microbial load was completed two days prior to all sensory panel dates. This was done in this manner as it takes 48 hours for the aerobic plates to process prior to human consumption of product during sensory. A 4 cm² area was cut out of a small square of aluminum foil for each tomato that was being swabbed and were sterilized with test tubes using an autoclave. Two swabs were completed per tomato, one swab was completed along the sliced edges of the side of the tomato while another swab was used to swab around the stem scar. After swabbing, the Q-Swabs were vigorously vortexed for 7 seconds to release the microorganisms trapped in the tip, and then serially diluted in the PBS solution where it was then plated on to the 3M Aerobic Plate Count and 3M Yeasts and Molds for the determination of the total aerobic microorganisms and yeasts and mold, respectively. Each sample was plated in duplicate and incubated following the manufacturer’s instructions. The films with a colony density between 25-250 were counted.
2.6 Photos and purge

At the start of each sensory sampling day from each treatment container a tomato was chosen that best represented the container for photographing. Pictures were taken on a Pixel 6 Pro camera and the tomatoes were staged inside of a Glendan photobox with a white background. The tomatoes were placed one at a time onto an extruded polystyrene tray that had a wax paper sheet laid on top. The container pulled for each sample set for the period had all tomatoes removed and disposed of before being placed onto the scale and allowed time for any liquids to settle out evenly in the bottom of the container. After this period the weight was recorded and then the initial weight of the empty container was subtracted from the new weight to determine amount of purge.
2.7 Colorimetric

Prior to samples being selected for sensory analysis, was measured using a Konica Minolta Chromameter CR – 400 model. Color was measured using L*, a*, b*, and ΔE. First the tomato was held in an assembled state where three color measurements were taken, one measurement was taken on the top curve near the stem scar, one was taken at a perpendicular angle to the side of the tomato, and the last was taken on the bottom curve near the blossom point. Then slices were pulled out from the assembled tomato to get internal color measurements. A slice was pulled 3 slices in from the stem scar for a top slice, a slice was pulled another 3 slices in from the top slice that was pulled for a middle slice, and finally a bottom slice was pulled 3 slices up from the blossom point. This would allow for a composite representation of what the whole tomatoes color could be expected to be. This was completed for three tomatoes from each treatment group for a total of nine tomatoes. From the values collected, averages were generated for each individual tomato with distinctions being made for external color and slice color composites. The slices used for color were then set aside for running texture analysis on the same slices.
2.8 Texture analysis

Texture analysis was completed on the same slices used for color. Texture analysis was completed using a TA.XT plus C model texture analyzer. A shear blade test was used as well as a 5mm flat tipped probe set to run a Texture Profile Analysis. Results were recorded and graphs generated to determine appropriate values. Data recorded was then used to match with the sensory output collected to determine if there was a correlation between sensorial data collected and mechanical data collection.

2.9 Sensory Analysis

Sensory samples were prepared by marking treatments with three digit randomized numerical codes, and the codes were randomly assigned during each testing period so that panelists could not guess what the treatments were. The reference sample R was a fresh tomato that was bought the morning of the sampling day. Treatment containers were brought into a sample preparation space where middle slices were taken out of tomatoes to be used for sensory. Slices were cut into quarters to allow for ample samples to be available to panelists. Two quarters were layered and placed onto a plain white paper plate, and this was done for all treatments.
as well as the reference sample R. Panelists were directed to sit inside a walled sensory booth and presented with the sensory ballot and samples were slide through a door for privacy. Panelists were asked to place their name on the top of the ballot for use later in statistical analysis. Panelists were supplied with napkins, a fork and knife, bottled water, expectorant cups with lids, a writing utensil, and the sensory ballot. Panelists were told to follow the directions on the ballot and that when they were finished with their ballot and samples to push the button in the booth the have their responses and remaining samples and trash collected from the booth. Panelists were asked to sign up for dates and time slots and were sent reminders two days before each sampling period was to occur. Data was taken from the sensory ballot and input into a simple table on excel and then also into JMP for statistical analysis. A copy of the ballot used is in the appendix below.
3. Results and Discussion

3.1 Purge

After each sampling period the weights of the containers were recorded after samples had been disposed of. The recorded weights at the end of each sampling period were compared back to the initial weights of the tomatoes that had been placed into the container and a percent weight change was calculated using the following equation:

\[
\frac{\text{Weight}_{f} - \text{Weight}_{i}}{\text{Weight}_{i}} \times 100 = \% \text{Change of weight (v/v)}
\]

With this the purge was tracked each week. Purge changes were not notable over the period of this study with most changes being between 1-2% of each. This can be seen in the figure below and from this you can see that the treatment group that had the in-package sachet also experienced the most purge over the period of the study. This is to be expected as the media used for ClO₂ generation will absorb free water in the container.
Figure 8 - Purge tracking over study length
3.2 Texture Analysis

Textural analysis was completed on tomatoes at the start of each testing period prior to sensory. Texture Profile Analysis and Shear Blade testing was completed, with the TPA test being done using a 5mm flat tipped probe. The Shear Blade tests did not show any significant findings until the sixth test period where it showed that at a 5% significance level there was significance in treatment between the control variable and the two treated variables where the control variable had a higher average firmness value than the two treated variables.

Upon completion of the TPA test with the 5mm flat tipped probe, there was no significance found among treatment groups. The only significant factor to stand out was location of probing with the columella being the most significant point followed by the top slices being most significant at this location of testing. This is to be expected due to the proximity to the stem scar of the tomato and it being known to have a higher firmness at this location. Data tables for the TPA tests can be found in the appendix section of this thesis. Figures for the shear blade results can be found below. Data points are missing for tomato 3 samples in the control due to issues during slicing of the tomato causing some slices to be unusable for some testing methods.
The data, as displayed in the figures below, shows that there aren’t any major differences between the control and the treatment groups for texture analysis.

The limited loss of texture over the period of the study was found to match studies such as the one performed by Lana, Tijskens, and van Kooten (Lana, M. M., Tijskens, & Kooten, 2005) as well as Wu and Abbott (Wu & Abbott, 2002). Both studies looked in part at how storage conditions affected texture of tomatoes and had similar results to this study. Both studies determined use of a flat tipped probe is the preferred probe tip, and this is backed up from a further study by a study of firmness testing completed by Lana et al. (LANA, MILZA M., TIJSKENS, DE THEIJE, DEKKER, & BARRETT, 2007). There were no notable deleterious effects that occurred due to ClO₂ exposure. Neither a loss of textural properties or phytotoxicity were observed and they were appearing as the normal untreated tomatoes were over the time period of the study.
Figure 9 - Top slice of tomato used for shear blade testing

Figure 10 - Middles slice of tomato used for shear blade testing
Figure 11 - Bottom slice of tomato used for shear blade testing

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(Table 1 – TPA analysis of tomato 1 top slices at 3 separate locations over all treatment types)
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(Table 2 – TPA analysis of tomato 1 middle slices at 3 separate locations over all treatment types)

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(Table 3 – TPA analysis of tomato 1 bottom slices at 3 separate locations over all treatment types)
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<td>88.54</td>
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<td>29.64</td>
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<tr>
<td>10</td>
<td>123.11</td>
<td>244.61</td>
<td>176.31</td>
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<td>13</td>
<td>637.76</td>
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</tr>
<tr>
<td>16</td>
<td>125.14</td>
<td>485.77</td>
<td>128.13</td>
</tr>
<tr>
<td>20</td>
<td>173.58</td>
<td>172.04</td>
<td>208.89</td>
</tr>
<tr>
<td>Averages</td>
<td>202.54</td>
<td>241.20</td>
<td>161.38</td>
</tr>
<tr>
<td>Stdv</td>
<td>193.53</td>
<td>153.93</td>
<td>81.81</td>
</tr>
</tbody>
</table>

(Table 4 – TPA analysis of tomato 2 top slices at 3 separate locations over all treatment types)

### Tomato 2 Middle

<table>
<thead>
<tr>
<th>Days</th>
<th>Mesocarp</th>
<th>Internal Pericarp</th>
<th>Columella</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Bulk</td>
<td>Bulk w/in-Pack</td>
</tr>
<tr>
<td>0</td>
<td>82.61</td>
<td>132.53</td>
<td>107.81</td>
</tr>
<tr>
<td>3</td>
<td>89.14</td>
<td>261.15</td>
<td>100.66</td>
</tr>
<tr>
<td>7</td>
<td>215.54</td>
<td>180.88</td>
<td>152.87</td>
</tr>
<tr>
<td>10</td>
<td>140.04</td>
<td>201.09</td>
<td>239.28</td>
</tr>
<tr>
<td>13</td>
<td>474.93</td>
<td>607.77</td>
<td>144.94</td>
</tr>
<tr>
<td>16</td>
<td>500.32</td>
<td>873.03</td>
<td>431.44</td>
</tr>
<tr>
<td>20</td>
<td>192.75</td>
<td>160.40</td>
<td>216.93</td>
</tr>
<tr>
<td>Averages</td>
<td>242.19</td>
<td>345.26</td>
<td>199.13</td>
</tr>
<tr>
<td>Stdv</td>
<td>174.78</td>
<td>283.36</td>
<td>114.75</td>
</tr>
</tbody>
</table>

(Table 5 – TPA analysis of tomato 2 middle slices at 3 separate locations over all treatment types)
### Tomato 2 Bottom

<table>
<thead>
<tr>
<th>Days</th>
<th>Mesocarp</th>
<th>Internal Pericarp</th>
<th>Columella</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Bulk w/in-Pack</td>
<td>Control</td>
</tr>
<tr>
<td>0</td>
<td>137.42</td>
<td>51.90</td>
<td>183.26</td>
</tr>
<tr>
<td>3</td>
<td>301.62</td>
<td>2255.84</td>
<td>201.84</td>
</tr>
<tr>
<td>7</td>
<td>123.17</td>
<td>55.59</td>
<td>280.92</td>
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<tr>
<td>10</td>
<td>113.12</td>
<td>224.34</td>
<td>131.01</td>
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<td>13</td>
<td>1635.82</td>
<td>2267.20</td>
<td>211.31</td>
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<td>16</td>
<td>1915.66</td>
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<tr>
<td>20</td>
<td>200.71</td>
<td>262.94</td>
<td>298.01</td>
</tr>
<tr>
<td></td>
<td>Averages</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>635.07</td>
<td>978.90</td>
<td>365.81</td>
</tr>
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<td></td>
</tr>
<tr>
<td></td>
<td>791.60</td>
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<td>457.09</td>
</tr>
</tbody>
</table>

(Table 6 – TPA analysis of tomato 2 bottom slices at 3 separate locations over all treatment types)

### Tomato 3 Top

<table>
<thead>
<tr>
<th>Days</th>
<th>Mesocarp</th>
<th>Internal Pericarp</th>
<th>Columella</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Bulk w/in-Pack</td>
<td>Control</td>
</tr>
<tr>
<td>0</td>
<td>318.36</td>
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</tr>
<tr>
<td>3</td>
<td>183.99</td>
<td>174.54</td>
<td>316.29</td>
</tr>
<tr>
<td>7</td>
<td>162.53</td>
<td>251.91</td>
<td>273.59</td>
</tr>
<tr>
<td>10</td>
<td>71.65</td>
<td>121.22</td>
<td>96.91</td>
</tr>
<tr>
<td>13</td>
<td>204.49</td>
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</tr>
<tr>
<td>16</td>
<td>167.16</td>
<td>166.89</td>
<td>257.67</td>
</tr>
<tr>
<td>20</td>
<td>206.42</td>
<td>196.54</td>
<td>174.94</td>
</tr>
<tr>
<td></td>
<td>Averages</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>187.80</td>
<td>193.56</td>
<td>221.42</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
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<td></td>
<td>73.30</td>
<td>45.56</td>
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</table>

(Table 7 – TPA analysis of tomato 3 top slices at 3 separate locations over all treatment types)
### Tomato 3 Middle

<table>
<thead>
<tr>
<th>Days</th>
<th>Control</th>
<th>Bulk</th>
<th>Bulk w/in-Pack</th>
<th>Control</th>
<th>Bulk</th>
<th>Bulk w/in-Pack</th>
<th>Control</th>
<th>Bulk</th>
<th>Bulk w/in-Pack</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>513.11</td>
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<td>874.77</td>
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</tr>
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<td>3</td>
<td>329.94</td>
<td>82.87</td>
<td>169.25</td>
<td>449.86</td>
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<td>170.02</td>
<td>420.10</td>
<td>252.49</td>
<td>469.44</td>
</tr>
<tr>
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<td>131.39</td>
<td>249.37</td>
<td>190.65</td>
<td>899.59</td>
<td>356.78</td>
<td>1413.32</td>
<td>1100.04</td>
<td>231.22</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>195.09</td>
<td>139.72</td>
<td>289.44</td>
<td>378.48</td>
<td>312.58</td>
<td>449.86</td>
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<td>139.40</td>
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</tr>
<tr>
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<td>411.13</td>
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<td>20</td>
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<td>209.09</td>
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<td>365.94</td>
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<td>258.11</td>
<td>428.82</td>
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<td>321.55</td>
<td>137.05</td>
<td>455.38</td>
<td>112.82</td>
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</tr>
</tbody>
</table>

(Table 8 – TPA analysis of tomato 3 middle slices at 3 separate locations over all treatment types)

### Tomato 3 Bottom

<table>
<thead>
<tr>
<th>Days</th>
<th>Control</th>
<th>Bulk</th>
<th>Bulk w/in-Pack</th>
<th>Control</th>
<th>Bulk</th>
<th>Bulk w/in-Pack</th>
<th>Control</th>
<th>Bulk</th>
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<td>0</td>
<td>171.95</td>
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<td>393.03</td>
<td>177.42</td>
<td>529.59</td>
<td>1027.34</td>
<td>488.11</td>
<td>4366.53</td>
<td>139.40</td>
</tr>
<tr>
<td>3</td>
<td>242.94</td>
<td>117.89</td>
<td>1314.81</td>
<td>519.67</td>
<td>357.30</td>
<td>135.67</td>
<td>420.10</td>
<td>252.49</td>
<td>469.44</td>
</tr>
<tr>
<td>7</td>
<td>67.94</td>
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<td>356.93</td>
<td>169.74</td>
<td>4419.52</td>
<td>1100.04</td>
<td>231.22</td>
</tr>
<tr>
<td>10</td>
<td>230.74</td>
<td>157.70</td>
<td>238.58</td>
<td>355.51</td>
<td>268.59</td>
<td>187.56</td>
<td>879.40</td>
<td>509.99</td>
<td>240.67</td>
</tr>
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<td>1361.75</td>
<td>98.77</td>
<td>588.16</td>
<td>545.49</td>
<td>249.77</td>
<td>396.58</td>
<td>260.48</td>
<td>221.22</td>
</tr>
<tr>
<td>16</td>
<td>1384.74</td>
<td>1419.24</td>
<td>1442.31</td>
<td>430.93</td>
<td>207.93</td>
<td>256.65</td>
<td>22.38</td>
<td>99.59</td>
<td>310.88</td>
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<td>217.02</td>
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<td>165.85</td>
<td>118.08</td>
<td>278.31</td>
<td>117.45</td>
</tr>
<tr>
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<td>555.46</td>
<td>617.84</td>
<td>448.47</td>
<td>325.05</td>
<td>194.21</td>
<td>879.40</td>
<td>509.99</td>
<td>240.67</td>
</tr>
<tr>
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<td>598.14</td>
<td>154.51</td>
<td>122.95</td>
<td>48.70</td>
<td>1570.56</td>
<td>395.42</td>
<td>127.44</td>
</tr>
</tbody>
</table>

(Table 9 – TPA analysis of tomato 3 bottom slices at 3 separate locations over all treatment types)
3.3 Color

Using the Minolta Chromameter to measure color it was found that there was no significant change to color being observed across any of the treatments over the course of the study. From what was observed, there was no statistical significance between the treated and the control. The tomatoes regardless of treatment type all maintained around the same color over the course of the study.

The L* values are in line with that seen in a study done by Oluk AC et al. (OLUK et al., 2019). They observed similar levels of color with a noted range of L* values of Red Beefsteak tomatoes averaging between 35.03 to 64.96 and a* values ranging from 0.86 to 41.03, with the average value for both L* and a* being 41.45 and 29.25 respectively. Bleaching effects were not found following the testing procedure of this study. This is notably not in line with similar studies that studied the effect of ClO₂ bleaching effects on tomatoes such as Mahovic et al. (Mahovic, Tenney, & Bartz, 2007). There are a few studies that indicate bleaching effects were not seen such as in studies completed by Goulter et al. (Goulter et al., 2023) and Sy, Murray, et al. (Sy, Murray, Harrison, & Beuchat, 2005).
Figure 12 - L* external readings over the course of the study

Figure 13 - L* sliced readings over the course of the study
Figure 14 - a* external readings over the course of the study

Figure 15 - a* sliced readings over the course of the study
Sensory was completed each sampling period, with participants being asked to answer questions based on sight, smell, taste, as well as personal preference of liking. Panelists were handed a reference sample in addition to each of the coded samples to compare to for the initial sensory based questions, this sample was a fresh tomato that was purchased that morning. The findings of this part of the study showed significance at two points during the study. At test day 3 there was significance found at a 5% level using a least square means Student’s t test showing that the treatment group that had undergone the bulk treatment with a follow up in package slow-release treatment, had a higher rating average then the treatment group that was strictly bulk treated at the start. This was with the bulk with extended sachet treatment option scoring a 0.56 and the bulk treated only treatment scoring a 1.67 on a scale of 0-4 with 0 being like extremely and 4 being dislike extremely.

Another point of significance was found on day 7, where a significant difference was noted between the bulk treated sample and the control sample, with the control sample being ranked lowest on the likeability scale, with the Bulk treated sample scoring an average rating of 1.14 and the control sample scoring an average of 1.89 on a scale of 0-4 with 0 indicating
like extremely and 4 indicating dislike extremely. All response averages can be seen in the charts below. The closer to 0 one gets the less difference is found between the treatments and the reference or in the case of preference, the closer to 0 the more liked the treatment is.

While on the surface it may seem that there was no importance, upon further examination the basis of no significance between the variables is what is in fact significant. This starts to show that while there is no immediate standout, that means that the treated variables is up in good consideration by the consumer with a untreated variant.

In a study by V.M. Gómez-López, F. Devlieghere, P. Ragaert, and J. Debevere (Gómez-López, V. M., Devlieghere, Ragaert, & Debevere, 2007) on shredded carrots exposed to gaseous ClO₂ looked at acceptability by consumers through use of a sensory panel. While the produce and length of study differs, we look at how the consumers reacted to the use of gaseous ClO₂ affected the consumers perception. While a bleaching effect was present in this study the panelists said that the only notable point was that of odor. The study found that treatment by gaseous ClO₂ did not affect or impair sensory attributes.
Figure 16 - Response averages of participants to color; Columns that share similar letters are not significantly different.

Figure 17 - Response averages of participants to aroma; Columns that share similar letters are not significantly different.
Figure 18 - response averages of participants to taste; Columns that share similar letters are not significantly different

Figure 19 - response averages of participants on overall preference/liking; Columns that share similar letters are not significantly different
4. Microbial Analysis

Microbial analysis was completed 3 days prior to consumption by the sensory panelists to get a full review of both aerobic as well as yeast and mold counts to be completed. Aerobic plate counts (APC) were completed using the 3M APC petrifilm and following all directions for storage and inoculation provided by 3M. Same was done for the Yeast and Mold petrifilm, which were also from 3M. APC petrifilm was incubated for 72 hours at 30°C while the yeast and mold petrifilm was incubated at 25°C for 48 hours per the directions given by 3M.

Data shown below indicates that the treated tomatoes were below the level of detection for most all the days of the study with minor exceptions being the first day and days towards the end of the study. By comparison to the control, the treated samples indicate that there is a significant difference for being treated versus untreated through this studies treatment method. Only on the last day is there no notable significance in aerobic counts between the treated samples compared to the control samples.

Yeast and mold counts were negligible through the length of the study and as such are not listed below. All counts for yeast and molds were found to be 0 over the course of the entire length of the study.
In a study by Gómez-López et al. (Gómez-López, V. M., Devlieghere, Ragaert, & Debevere, 2007), microbial analysis indicated that there was a much slower rate of growth present on produce treated by gaseous ClO\textsubscript{2} then the control. In a separate study by Ling Wang, Kimberly Sokorai, Vivian C.H. Wu, and Xuetong Fan (Chai, Hwang, Huang, Wu, & Sheen, 2020b) where they inoculated grape tomatoes, they also saw a drastic drop in the level of CFU from untreated to treated samples to that of what was seen in our study.

Figure 20 - Total Aerobic count from the stem scar location over course of the study
Figure 21 - Total Aerobic count along the cut side of the tomato over the course of the study
5. Conclusion

This study has demonstrated that it is feasible to use ClO$_2$ and consumers will still readily choose to consume it over a standard tomato slice. The data shows that with little significant change being found amongst texture changes over time across the layers of the tomato slices, nor any significant changes to the color of the tomato that were concerns of other studies done within this vein. The application this study brings could allow for an extension of the shelf life of the tomato, reducing food waste within food service without a considerable change to consumers perception of the product.
The limitations of this study would be that storage information prior to purchase from Publix was not able to be provided upon request nor what sort of treatments the tomato might have gone through at their packing facility prior to transportation. This study was focused on looking at the sensorial effects of ClO$_2$ and the perception of it by the consumer, however information relating to vitamin content as well as possible lycopene content were not a part of the purview of this study and would be a good addition to understanding the effects on the nutritional changes that could possibly be undergone from this treatment.
APPENDIX

APPENDIX I

§51.1855 – U.S. No. 1.

Consist of tomatoes which meet the following requirements:

(a) Basic Requirements:
   a. Similar varietal Characteristics;
   b. Mature;
   c. Not overripe or soft;
   d. Clean;
   e. Well developed;
   f. Fairly well formed; and,
   g. Fairly smooth.

(b) Free from:
   a. Decay;
   b. Freezing injury; and
   c. Sunscald.

(c) Not damaged by any other cause

(d) For tolerances see §51.1861

§51.1856 – U.S. Combination
“U.S. Combination” consists of a combination of U.S. No. 1 and U.S. No. 2 tomatoes: **Provided**, That at least 60 percent, by count, meet the requirements of U.S. No. 1 grade.

(a) For tolerances see §51.1861

§51.1857 – U.S. No. 2.

“U.S. No. 2.” Consists of tomatoes which meet the following requirements:

(a) Basic requirements:
   a. Similar varietal characteristics;
   b. Mature;
   c. Not overripe or soft;
   d. Clean;
   e. Well developed;
   f. Reasonably well formed; and,
   g. Not more than slightly rough.

(b) Free from:
   a. Decay;
   b. Freezing injury; and,
   c. Sunscald.

(c) Not seriously damaged by any other cause

(d) For tolerances see §51.1861
§51.1858 – U.S. No. 3

“U.S. No. 3.” Consists of tomatoes which meet the following requirements:

(a) Basic requirements:
   a. Similar varietal characteristics;
   b. Mature;
   c. Not overripe or soft;
   d. Clean;
   e. Well developed; and,
   f. May be misshapen.

(b) Free from:
   a. Decay; and,
   b. Freezing injury

(c) Not seriously damaged by:
   a. Sunscald;

(d) Not very seriously damaged by any other cause

(e) For tolerances see §51.1861

This information provided by the USDA also gives detailed information on color classification for tomatoes as provided by §51.1860 as follows:
§51.1860 – Color Classification

(a) The following terms may be used, when specified in connection with the grade statement, in describing the color as an indication of the stage of ripeness of any lot of mature tomatoes of a red fleshed variety:

a. Green. “Green” means that the surface of the tomato is completely green in color. The shade of green color may vary from light to dark;
b. Breakers. “Breakers” means that there is a definite break in color from green to tannish-yellow, pink or red on not more than 10 percent of the surface;
c. Turning. “Turning” means that more than 10 percent but not more than 30 percent of the surface, in the aggregate, shows a definite change in color from green to tannish-yellow, pink, red, or a combination thereof;
d. Pink. “Pink” means that more than 30 percent but not more than 60 percent of the surface, in the aggregate, shows pink or red color;
e. Light Red. “Light Red” means that more than 60 percent of the surface, in the aggregate, shows
pinkish-red or red: Provided, That not more than 90 percent of the surface is red color; and,

f. Red. “Red” means that more than 90 percent of the surface, in the aggregate, shows red color.

(b) Any lot of tomatoes which does not meet the requirements of any of the above color designations may be designated as “Mixed Color”.

(c) For tolerances see §51.1861

(d) Tomato color standards U.S.D.A. Visual Aid TM- L-1 consists of a chart containing twelve color photographs illustrating the color classification requirements, as set forth in this section. This visual aid may be examined in the Fruit and Vegetable Division, AMS, U.S. Department of Agriculture, South Building, Washington, D.C. 20250; in any field office of the Fresh Fruit and Vegetable Inspection Service; or upon request of any authorized inspector of such Service.

A copy of the above-mentioned color standards chart will be listed below for better understanding of the USDA’s Color Classification of Tomatoes.
Figure 22 - Color Classification Chart from the USDA
The USDA has also listed definitions for the terms that were used in its classification of tomatoes as listed below:

§51.1864 Similar varietal characteristics

“Similar varietal characteristics” means that the tomatoes are alike as to firmness of flesh and shade of color (for example, soft-fleshed, early maturing varieties are not mixed with firm-fleshed, midseason or late varieties, or bright red varieties mixed with varieties having a purplish tinge).

§51.1865 Mature

“Mature” means that the tomato has reached the stage of development which will insure a proper completion of the ripening process, and that the contents of two or more seed cavities have developed a jelly-like consistency and the seeds are well developed.

§51.1866 Soft

“Soft” means that the tomato yields readily to slight pressure.

§51.1867 Clean

“Clean” means that the tomato is practically free from dirt or other foreign material
§51.1868 Well developed

“Well developed” means that the tomato shows normal growth. Tomatoes which are ridged and peaked at the stem end, contain dry tissue, and usually contain open spaces below the level of the stem scar, are not considered well developed.

§51.1869 Fairly well formed

“Fairly well formed” means that the tomato is not more than moderately kidney-shaped, lop-sided, elongated, angular, or otherwise moderately deformed.

§51.1870 Fairly smooth

“Fairly smooth” means that the tomato is not conspicuously ridged or rough

§51.1871 Damage

“Damage” means any specific defect described in §51.1877, Table II; or an equally objectionable variation of any on of these defects, any other defect, or any combination or defects, which materially detracts from the appearance, or the edible or marketing quality of the tomato.

§51.1872 Reasonably well formed
“Reasonably well formed” means that the tomato is not decidedly kidney-shaped, lop-sided, elongated, angular, or otherwise decidedly deformed.

§51.1873 Slightly rough

“Slightly Rough” means that the tomato is not decidedly ridged or grooved.

§51.1874 Serious damage

“Serious damage” means any specific defect described in §51.1877, Table II; or an equally objectionable variation of any one of these defect, any other defect, or any combination of defects, which seriously detracts from the appearance, or the edible or marketing quality of the tomato.

§51.1875 Misshapen

“Misshapen” means that the tomato is decidedly kidney-shaped, lop-sided, elongated, angular or otherwise decidedly deformed: Provided, That the shape is not affected to an extent that the appearance or the edible quality of the tomato is very seriously affected.

§51.1876 Very serious damage

“Very serious damage” means any specific defect described in §51.1877, Table II; or an equally objectionable variation of any one of these defects, any other defect, or any combination of defects, which very
seriously detracts from the appearance, or the edible or marketing quality of the tomato.

These were all standards for grades for fresh tomatoes as provided by the USDA, however there are also three other types of grading provided by the USDA under the United States Consumer Standards for Fresh Tomatoes labeled §51.1900 - §51.1913.

§51.1900 General

These standards apply only to field grown tomatoes and not to tomatoes grown in greenhouses.

§51.1901 U.S. Grade A.

U.S. Grade A shall consist of tomatoes of similar varietal characteristics which are mature and are at least turning, but are not overripe or soft which are well developed, at least fairly well formed, fairly smooth, free from soft rot, freezing injury, and from damage caused by dirt, bruises, cuts, shriveling, sunscald, sunburn, puffiness, catfaces, growth cracks, scars, dry rot, other diseases, insects, hail, or mechanical or other means. Tomatoes on the shown face shall be reasonably representative in size and quality of the contents of container
(a) Incident to proper grading and handling, except for maturity, not more than 5 percent, by count, of the tomatoes in any lot may fail to meet the requirements of the grade, including not more than 1 percent for tomatoes which are affected by soft rot.

§51.1902 U.S. Grade B.

U.S. Grade B shall consist of tomatoes of similar varietal characteristics which are mature and are at least turning, but are not overripe or soft and not badly misshapen; which are free from soft rot, freezing injury and from serious damage caused by dirt, bruises, cuts, shriveling, sunscald, sunburn, puffiness, catfaces, growth cracks, scars, dry rot, other diseases, insects, hail, or mechanical or other means. Tomatoes on the shown face shall be reasonably representative in size and quality of the contents of the container.

(a) Incident to proper and handling, except for maturity, not more than 5 percent, by count, of the tomatoes in any lot may fail to meet the requirements of the grade, including not more than 1 percent for tomatoes which are affected by soft rot.

§51.1905 Off-Grade tomatoes

Tomatoes which fail to meet the requirements of either of the foregoing grades shall be Off-Grade tomatoes.
Theses are all grades for tomatoes that are for fresh field grown tomatoes, and as of 2007 there is a complete set of standards for fresh tomatoes grown in a greenhouse listed under United States Standards for Grades of Greenhouse Tomatoes, with the grades being specifically explained under §51.3345 & §51.3346.

§51.3345 U.S. No. 1.

“U.S. No. 1” consists of tomatoes of similar varietal characteristics which are mature but not overripe or soft, clean, fairly well formed; which are free from decay, sunscald, and freezing injury, and free from damage caused by bruises, cuts, shriveling, puffiness, catfaces, growth cracks, scars, disease, insects, moldy stems, skin checks, or other means.

§51.3345 U.S. No. 2.

“U.S. No. 2” consists of tomatoes of similar varietal characteristics which are mature but not overripe of soft, clean, reasonably well formed; which are free from decay, sunscald, and freezing injury, and free from serious damage caused by cuts, shriveling, puffiness, catfaces, growth cracks, scars, disease, insects, moldy stems, skin checks, or other means.
APPENDIX II

Sec. 173.300 Chlorine dioxide

Chlorine dioxide (CAS Reg. No. 10049-04-4) may be safely used in food in accordance with the following prescribed conditions:

(a) (1) The additive is generated by one of the following methods:

   (i) Treating an aqueous solution of sodium chlorite with either chlorine gas or a mixture of sodium hypochlorite and hydrochloric acid.

   (ii) Treating an aqueous solution of sodium chlorate with hydrogen peroxide in the presence of sulfuric acid.

   (iii) Treating an aqueous solution chlorite by electrolysis.

(2) The generator effluent contains at least 90 percent (by weight) of chlorine dioxide with respect to all chlorine species as determined by Method 4500-C102 E in the “Standard Methods for the Examination of Water and Wastewater,” 20th ed., 1998, or an equivalent method. Method 4500-C102 E (“Amperometric Method II”) is incorporated by reference in accordance with 5 U.S.C. 552(a) and 1 CFR part 51. You may obtain a copy from the Office of Food Additive Safety (HFS-200), Center for Food Safety and Applied Nutrition, Food and Drug
The additive may be used as an antimicrobial agent in water used in poultry processing in an amount not to exceed 3 parts per million (ppm) residual chlorine dioxide as determined by Method 4500-C102 E, referenced in paragraph (a)(2) of this section, or an equivalent method.

The additive may be used as an antimicrobial agent in water used to wash fruits and vegetables that are not raw agricultural commodities in an amount not to exceed 3 ppm residual chlorine dioxide as determined by Method 4500-C102 E, referenced in paragraph (a)(2) of this section, or an equivalent method. Treatment of the fruits and vegetables with chlorine dioxide shall be followed by a potable water rinse or by blanching, cooking, or canning.

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