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The Real Cost of Titanium Dioxide in Food

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Abstract: Research has shown that the adverse effects of consuming TiO_2 NP are concerning; these particles accumulate in the body over time, potentially leading to a variety of harmful outcomes including genotoxicity, neurological damage, and psychological impacts. Adolescents are particularly at risk, since they consume snacks, candies, and processed foods that contain TiO_2 the most. The compound is used for its bright, white, and smoothening qualities, making products appear more visually appealing. However, these benefits can lead to long-term health issues. Despite the significant quantity of evidence emphasizing their dangers, there is a lack of federal regulation in the US on their use in food, and food labeling is typically unclear about the presence of TiO_2 to consumers. In contrast, the European Food Safety Authority (EFSA) recognized these risks and banned the use of TiO_2 in the European Union in August 2022.

To better understand how adolescents perceive TiO_2 NPs before and after educating, we conducted a survey with 409 responses from students in our school and neighborhood. Using statistical analysis, we found a significant association between the factors adolescents prioritize when buying snacks and their reactions after learning more about the potential health risks of TiO_2. Furthermore, the adolescents who expressed greater concern about their consumption of TiO_2 were also those who prioritized taste over appearance when purchasing snacks. This information is important for public health advocacy, as it demonstrates that removing TiO_2 from food products would not negatively impact the satisfaction of consumers.

Additionally, we designed and carried out a single-blind experiment using pre and post-surveys about our educational presentation on TiO_2. The results showed that awareness plays a crucial role in shaping informed decision making. Many participants who had initially little knowledge of TiO_2 significantly shifted their attitudes after receiving clear and accessible information. This data supported the idea that public education can reduce consumption of harmful additives. To optimize educating people, we created a website showing findings of TiO_2's health risks, scientific research findings, and current policy actions, making it more accessible to both adolescents and the general public.

Furthermore, we conducted interviews with three experts within public health and regulatory policy who contributed to the papers we analyzed. We discussed EFSA's decision-making process, the scientific reasoning behind the ban in Europe, and the political and economic barriers to similar actions in the United States, particularly in New York City. Moreover, we explored the potential of implementing mandatory warning labels as initial steps before a federal ban could be considered in a follow-up interview with one expert.

This project is on-going with the goal of continuing raising awareness and advocating for stronger policy changes on the federal level. The European Union's actions show that regulating TiO_2 is both possible and practical. By combining our experimental results, we hope to contribute to prioritizing health over appearance in the food industry. Ultimately, our goal is to ensure that adolescents and consumers can make informed choices based on sound scientific facts.

Author keywords: Titanium-Dioxide; Nanoparticles; Genotoxic; Neurological; Psychological

Introduction

Titanium dioxide (TiO_2) is a pigment and additive in cosmetics, pharmaceuticals and food, discovered in the late 18th century, and approved in the 1960s by the Food and Drug Administration (FDA).[1] There are three synthetically occurring TiO_2 polymorphs (existing in more than one crystalline form): monoclinic, tetragonal, and orthorhombic ramsdellite-like. However, anatase and rutile are the primary forms used in commercial products, with anatase being more prevalent in food and pharmaceuticals due to its brightening properties.[2] TiO_2 was mass produced and became a staple in the early 20th century, especially in candies, chewing gum, baked goods, and dairy products. For example, Fig. 1 below shows one of such products.

In the food industry, it is used as a white color and smooth color enhancer.[1] As a result, we suspect adolescents are highly exposed to TiO_2 NPs due to their frequent consumption of processed snacks, candies and dairy products. Despite the FDA allowing the use of TiO_2 as safe in food, the nanoparticles (NPs) disrupt gut health, and trigger inflammation by gathering in the organs. With the growing concern

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Figure 1. Candies potentially containing TiO_2

of the adverse long term effects, the European Union (EU) has banned it specifically as a food additive.[2] Through exposure to TiO_2 NPs, adolescents can experience genotoxicity, neurotoxicity, and psychological reactions making this a pressing social and health issue.[1,2]

A major contributing factor to the main reason of concern for TiO_2 is its size. When used, it is typically manufactured in nanoparticles (NPs), which contribute to the opacity (ability to block light). This is the main reason why it is used in food products as it produces a shiny look. TiO_2 NPs need to be approximately between 200 and 300 nanometers in diameter—half the size of visible light waves—allowing them to reflect light in multiple directions.[3] Smaller TiO_2 nanoparticles have an increased surface area compared to its larger counterparts. The International Agency for Research on Cancer (IARC) labeled it as "possible carcinogen to humans". The agency also raises a similar question of its genotoxicity, since DNA damage may have resulted in somatic mutations in the initiation step of cancer progression.[4]

Genotoxic effects

Concerns about genotoxicity are associated with TiO_2 NPs—the ability of a substance to damage DNA—adversely affecting DNA leading to potentially harmful cellular damage. Ghosh et al.[5] revealed that TiO_2 NPs are more genotoxic compared to larger particles, due to their ability to penetrate cells more easily, both in the nucleus and cytoplasm. Particularly, the anatase form of TiO_2 NP has been shown to trigger more detrimental effects than other crystalline forms, such as rutile. Despite the difference, both forms still potentially induce adverse health effects. Furthermore, TiO_2 NPs can impair cellular DNA repair mechanisms, by inactivating the nucleotide excision repair and base excision repair pathways, which are essential for correcting DNA damage. Short term exposure to TiO_2 NPs can increase the production of reactive oxygen species, leading to oxidative stress, cell death, and DNA damage.[5] However, long-term exposure can cause chromosomal instability and cell transformation further increasing the risk of cancer development, loss of cellular function, and genetic mutations.

Neurological effects

Another concern regarding TiO_2 NPs is the potential neurotoxicity, as long-term exposure can adversely affect the Central Nervous System. Gui et al.[6] conducted an experiment in 2004 testing the effect TiO_2 NPs has on the hippocampal neuroinflammation in mice, and they examined the severity of memory and attention loss. The mice in the three treatment groups, compared to the control group, exhibited an over-proliferation of glial cells (abnormal growth of glial cells), necrosis (cell death), abscission of perikaryon (separation and injury to the cell), shrinkage of cell volume, and nuclear irregularity;[6] causing impaired spatial memory and reduced physical activity. These results suggest similar human health effects may occur, as the genetic makeup of mice and humans share similarities.

Psychological effects

The potential ability of TiO_2 NPs' to cross the blood-brain barrier raises concerns about their potential impact on mental health.[7] Once in the brain, TiO_2 NPs can induce oxidative stress, promote neuroinflammation, and disrupt brain biochemistry, ultimately impairing neuronal function and structure.[7] Oxidative stress damages cells by creating an imbalance of harmful molecules, while neuroinflammation is the brain's immune response that, if prolonged, can lead to cognitive decline. Disrupting brain biochemistry affects neurotransmitters, potentially impairing learning, memory, and mood. These effects may contribute to psychological disorders and could play a role in the development of neurodegenerative conditions, such as Alzheimer's or Parkinson's disease.[7] The severity of neuronal damage caused by TiO_2 NPs depends on the particle dose and the particle size as smaller particles are more likely to penetrate deeper into tissues.[7] Furthermore, this poses a significant risk for anyone who commonly use sunscreen, cosmetics, or food products, which contain TiO_2

NPs and this could interfere with cognitive functions and memory. Particularly pregnant women, fetuses, infants, and adolescents are vulnerable to these effects as their brains are in critical stages of development.

Laws and government regulations

To proactively address potential health concerns, the EU banned TiO_2 as a food additive in January 2022.[8] Regulated by the European Food Safety Authority (EFSA), the ban indicates that it may be unsafe for consumption in food products.[8] Under current European Commission rules, foods containing nanoparticles should be labeled accordingly. In contrast, U.S. regulations allow manufacturers to omit TiO_2 from labels due to legislative exceptions, such as when additives serve no function or make up less than 25% of the final product.[8] Also $TiO_2$is sometimes classified as

a manufacturing aid, further exempting it from having to declare them on labels.[8]

On average, TiO_2 NP in food are 110 nm, with at least 36% under 100 nm and a particle range of 30 to 400 nm.[9] Their small size allows them to potentially accumulate in organs like the liver and brain.[9] Yet, in the U.S., such formations don't meet the current criteria for nanotechnology labeling. Since TiO_2 NPs remain registered as an inactive ingredient, manufacturers can continue using it without disclosure.[8]

Though TiO_2 appears on the FDA's GRAS (generally recognized as safe) list, some have questioned its safety due to the potential long-term adverse effects.[10] Specifically, GRAS allows companies to self-certify ingredients without FDA review, meaning substances like TiO_2 NPs can enter the market without full oversight.[10] The FDA cannot re-evaluate these additives unless harm is proven, limiting its regulatory power.

The lack of oversight and check and balances affects adolescents, who often choose snacks based on taste and appearance, unaware they contain TiO_2.[10] We hypothesized that improving labeling, public awareness, and stricter regulations, such as those developed in the EU's approach, could influence consumer choices and promote safer alternatives.

Description/Methodology/Proposed Research Approach

Ultimately, TiO_2 NPs could cause neurological damage, cell degeneration, behavioral disorders, memory issues, etc., in the future with prolonged exposure. The exact number remains unknown as every individual exhibits different bodily functions. Our field research aimed to identify whether consumption rates were highest among adolescents and to examine the relationship between their understanding of TiO_2 NPs in food products and how this knowledge influenced their food choices. From our results, we hypothesized that those who know more about the TiO_2 food additive are less likely to consume foods that contain it.

Our research survey consisted of two questionnaires. The first questionnaire was a voluntary survey with 9 questions. The parameter of interest was all adolescents ranging from 12 to 20 years old. Within these questions, there were four main categories: consumption habits (consumption of processed snacks and how frequently), snack choice influences (most important factor and checking of ingredient labels), awareness and understanding (heard of TiO_2 and whether they know its use), and the behavior and risk attitudes (scientific studies and EU ban). The sample consisted of 409 adolescents from various schools. To carry out our study, we asked teachers to post the survey in their google classrooms, created posters that were hung up all over our neighborhood in Brooklyn, NY as well as in nearby stores, and posted it in community group chats for the programs we participate in. We employed the methods mentioned above in an effort to increase the response rate (people of different socioeconomic backgrounds).

To determine whether there was a relationship between the factors adolescents prioritize when purchasing snacks and their response to health information about TiO_2, a Pearson correlation analysis was conducted at a significance level of 0.05. The null hypothesis stated that there is no linear correlation between these variables, while the alternative hypothesis proposed a significant association. Although the randomness condition was not fully met due to the voluntary nature of the survey, the independence condition was satisfied since only one response per participant was allowed. The results showed a Pearson correlation coefficient of $r = 0.38$ with a p-value $= 0.0006$ ($n = 409$), indicating a moderate, statistically significant positive correlation between the factors adolescents value in snacks and how they responded after learning about TiO_2's health risks. 189 adolescents reported they would avoid TiO_2 after understanding its long-term effects, and most of them (108 or 57.1%) prioritized taste over appearance. This suggests that appearance-enhancing additives like TiO_2 are unnecessary, as consumer preferences are more strongly driven by taste. While some limitations exist due to non-random sampling, the large sample size ($n = 409$) strengthens the reliability of the findings.

Our second questionnaire was distributed during the single-blind experiment, in which 24 participants from school clubs (Health Without Barriers, Glamour Gals, and Medical Club) took part. The experiment began with a pre-survey assessing prior knowledge of TiO_2 and participants' ability to identify its presence in gummy samples based on appearance and taste. This survey consisted of 6 questions.

Results of our findings

Firstly, we interviewed a prominent city council member from our district. The council member is a health professional, and she held a position on the Chair of the City Council's Committee (NY) on Hospitals, but had no prior knowledge on the issue. Our interview was conducted through email and consisted of an intersection of public health policy and food safety regulation, specifically regarding the use of TiO_2 NPs as a food additive. Based on the issues identified in our research, the questions were phrased to suggest possible future actions without bias. The council member mentioned that food safety regulations are largely governed at the federal level, but local governments can advocate for stricter regulations and help ensure that our communities stay informed and educated about the harmful food additive: TiO_2 NPs. Council members' office specifically prioritizes food safety by staying informed on emerging health concerns and working with health experts to address issues that affect our community's well-being. Furthermore, to educate the public if concerns about TiO_2 NPs gain traction in the community, the council member suggested holding community forums and collaborating with public health organizations to share information and highlighted that education is key to ensuring that constituents are aware of potential risks and know where to turn for more information. Additionally, council member's office could initiate petitions, gather public support, and work with other lawmakers to push for stricter regulations at the state or federal level. Previously, the council member had supported initiatives to improve food labeling and advocated for stronger

consumer protection laws to ensure public safety, and she routinely works closely with healthcare professionals to address concerns within our community.

Following this, we interviewed Dr. Paul Westerhoff, a researcher at Arizona State University via Zoom call. During the interview, he specifically talked about the potential negative aspects of completely substituting TiO_2 NPs. TiO_2 NPs is not only used as a whitening agent, but also as a smooth buttery texture. TiO_2 NPs are currently mixed with oils/-fats to produce the desired texture. However, if we were to completely substitute TiO_2 with fats and oils, that wouldn't necessarily be much more beneficial. Alternatively, if we were to replace TiO_2 with a different chemical, that also may not be very beneficial. TiO_2 has been continuously used since the 1900s and therefore, there is a lot of research concerning the chemical which can be the same for any potentially new chemicals. Although he talked about the potential negatives of banning TiO_2 completely, he did say that banning the NP form could be beneficial. If we were to keep the particles to a size that would exceed the NP metrics, then the risk of the adverse effects would decrease as less particles would accumulate in our body.

Lastly, we interviewed Dr. Gabriele Aquilina,[11] a specialist in genotoxicology, who works for the EFSA (European Food Safety Authority). We conducted the interview via Google Call to gain insight into how food additives, including TiO_2, are regulated and assessed in the European Union as well as the genotoxic aspects. He explained that EFSA is composed of several expert panels, each focused on a specific area. For several years, he served as a member of the panel on food additives and the products that use them. He emphasized that monitoring the safety of food additives is critical not only for human health, but also for animal health, as animals contribute to the food supply through products like milk, eggs, and meat. Dr. Aquilina described the EFSA's process for evaluating food additives. He and his colleagues receive documents containing all available studies on the additive. Based on this information, they are responsible for drafting an official opinion on whether the additive is considered safe for human consumption. If the panel determines that further information is needed or if the additive is found to be unsafe, restrictions are recommended. He clarified that EFSA doesn't perform laboratory tests itself. Instead, it receives test data from laboratories that are under strict regulation of authority. These labs provide complete study reports, which the EFSA panel carefully reviews to assess the reliability of the studies and determine whether the evidence is sufficient to draw conclusions. Regarding nanoparticles, Dr. Aquilina noted that the study of their toxicity is a relatively recent development, emerging as a significant concern around 2015. He explained that nanoparticles, due to their extremely small size, can enter cells through a process called endocytosis: the method by which cells engulf particles from their environment using their cell membrane. Once inside, some nanoparticles remain in the cytoplasm, while others can enter the nucleus and potentially come into contact with DNA. His expertise provided an understanding of how regulatory assessments are made and why nanoparticles, like TiO_2, have become a growing focus in food safety discussions.

Our first questionnaire was voluntary, thus there is possibly response bias as people choose to participate due to having strong opinions, more interest, or more awareness of the topic. This survey consisted of 9 questions. Responses of survey participants are shown through pie chart in Appendix A. Furthermore, due to the geographic location, the way we distributed the survey, and type of community survey, possible bias may arise. This may result in an overestimate or underestimate of the population. 15.4% were ages 12–14, 73.8% were ages 15–17, and 10.8% were ages 18–20. Of the 409 people sampled, 85.1% had not heard of TiO_2 before this survey. When purchasing snacks, 64.8% chose taste to be the most important factor for them, while only 2.4% chose appearance to be the most important factor for them. This indicates that the people surveyed did not value appearance. Contrary to what companies seem to believe, appearance and texture are more important to consumers. Fifty-seven-point seven percent consume dairy-based desserts, 50.1% consume chewing gum, and 39.1% consume candy at least once a week. Overall, 46.5% consume processed snacks a few times a week and 24.2% consume processed snacks multiple times a day. When informed of the risks of TiO_2 NP, 46.2% said that they would try to avoid brands known to include TiO_2 NP. 47.2% said that they would reduce their consumption of these brands and foods known to include it. Knowing that the European Union banned it, 62.1% think that the FDA should ban TiO_2 NPs as well. Additionally, it should be noted the language used to inform people could also act as a source of possible bias.

Figures in Appendix B show the results of second survey. Before the presentation, 66.7% of respondents had never heard of TiO_2, and 50% reported that knowing an ingredient is labeled as a "possible carcinogen" would influence their decision to consume it. Additionally, 50% believed that most food additives are unsafe. After learning about TiO_2, participants voluntarily sampled two types of gummy bears: Sample A (Haribo, containing TiO_2 NPs) and Sample B (organic, TiO_2-free). In the post-survey, 70.8% of participants correctly identified Sample A as the one containing TiO_2, primarily due to its shinier appearance. Furthermore, 79.2% of responders noticed a taste difference between the two samples, and 50% used both taste and appearance to make their conclusion. Importantly, all participants (100%) agreed that food brands should explicitly label whether their products contain TiO_2, demonstrating increased demand for transparency. Moreover, 83.3% of participants believe that brands should completely ban the use of TiO_2 NPs, reflecting more concern after being informed.

Discussions and Recommendations for Future Work

These findings suggest that increasing awareness through education significantly impacts consumer perception, encouraging individuals to make more informed decisions about the food they consume. This also highlights a broader

public desire for greater labeling transparency and potential policy change regarding TiO_2. As of August 2022, the EU banned the use of TiO_2 NPs in food products, though they remain permitted in other industries. We recommend the US policymakers consider evidence showing TiO_2 NP's potential adverse health effects and consider regulating food additives that are potentially harmful to human health. Since the adverse health effects are primarily linked to the nanoparticle form, banning only TiO_2 NPs would reduce harm while keeping food formulations largely unchanged. While potential substitutes do exist such as oils and fats, they may not offer clear health benefits, making a targeted NP ban the most effective approach.

Furthermore, the field research indicates a strong association between awareness and avoidance of TiO_2-containing products. While education helps, it does not reach everyone. A warning label could encourage consumers to make informed decisions.

Conclusions

Our research found a significant link between adolescents' snack choices and their awareness of (TiO_2) NP; most prioritized taste over appearance, indicating that TiO_2's whitening effect is unnecessary for consumer satisfaction. After learning about its health risks, nearly half said they would avoid products containing it, and all participants supported clever labeling. Interviews with Council Member Mercedes Narcisse,[12] researcher Paul Westerhoff,[13] and EFSA toxicologist Gabriele Aquilina emphasized the importance of public education, the potential benefits of banning only the nanoparticle form, and the scientific reasoning behind the EU's regulatory actions. A literature review has shown that consuming TiO_2 NPs may produce genotoxic, neurotoxic, and psychological impacts TiO_2 NPs can have on adolescents. We researched the difference in risk depending on the particle size and the overall regulation of this product world wide. Our recommendations would help to restrict TiO_2 NPs within the US, and create warning labels. We recommend policymakers consider these adverse health effects and consider passing legislation regarding potential harmful food additives. While educating individuals did prove a lower likelihood to consume products with TiO_2 NPs, it is impossible to reach everyone. Other communities can also replicate my project by visiting our website and finding our information. Furthermore, they can replicate our experiments and reach out to us for more information. We envision that we would be able to communicate with other communities replicating our project, to ensure other communities have all necessary information at their disposal to replicate our implementation.

Acknowledgment

We sincerely acknowledge the support of Council Member Narcisse Mercedes, Paul Westerhoff, a researcher at Arizona State University, and Gabriele Aquilina, a specialist in genotoxicology who works for the EFSA (European Food Safety Authority) with data used in this study.

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Appendix A: Response to Questions in the First Survey

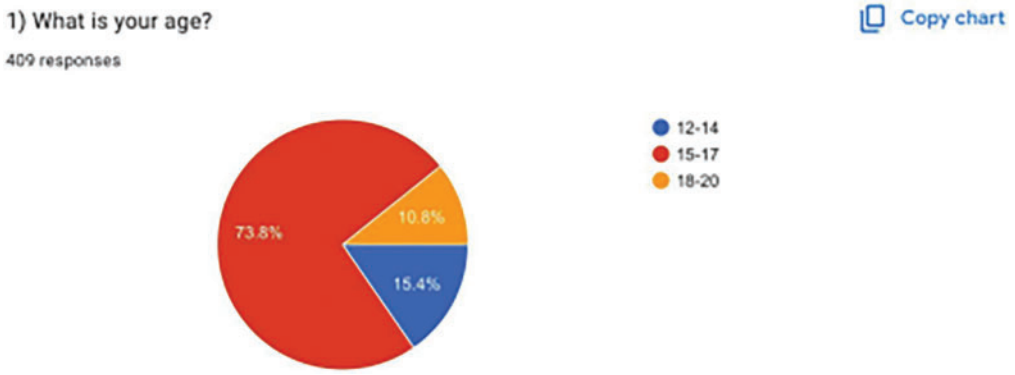

Figure 2. Response to Question 1 in the First Survey: "What is your age?"

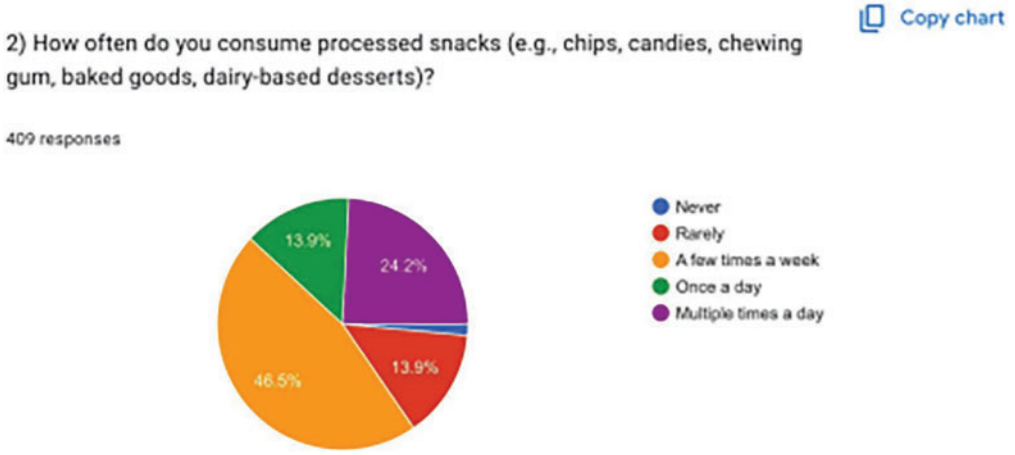

Figure 3. Response to Question 2 in the First Survey: "How often do you consume snacks (e.g., chips, candies, chewing gum, baked goods, dairy-based desserts)?"

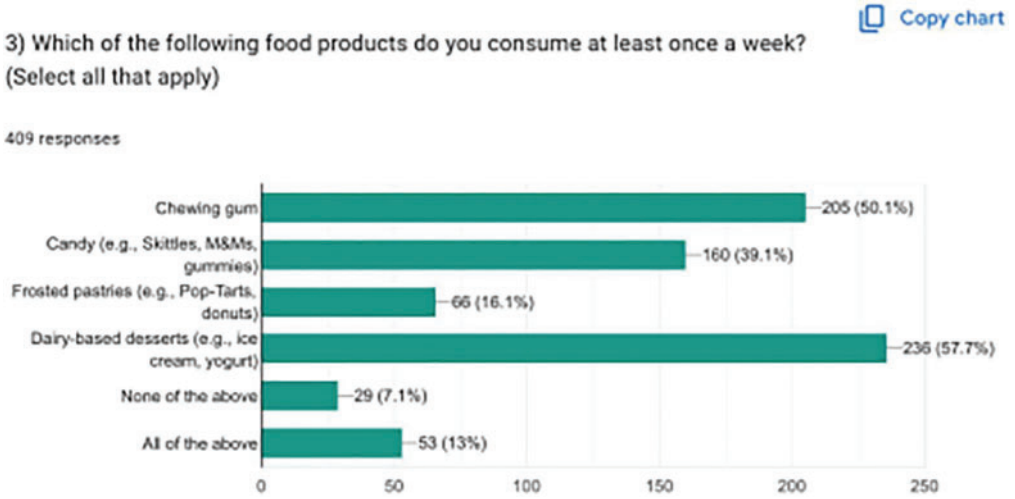

Figure 4. Response to Question 3 in the First Survey: "Which of the following food products do you consume at least once a week?"

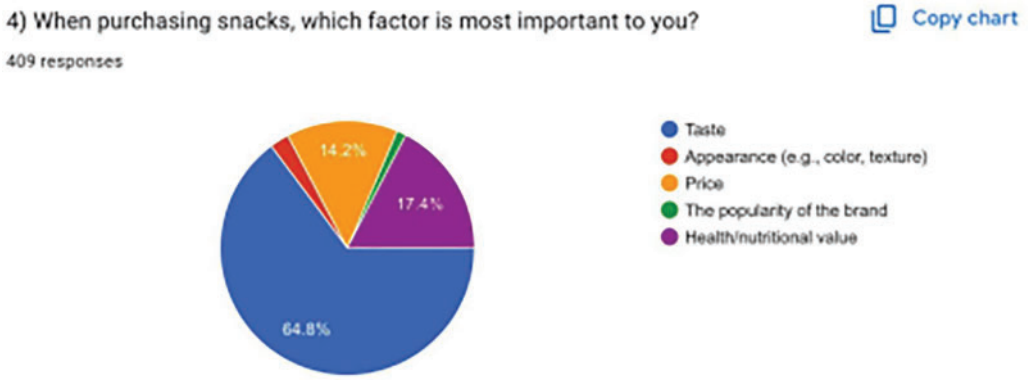

Figure 5. Response to Question 4 in the First Survey: "When purchasing snacks, which factor is the most important to you?"

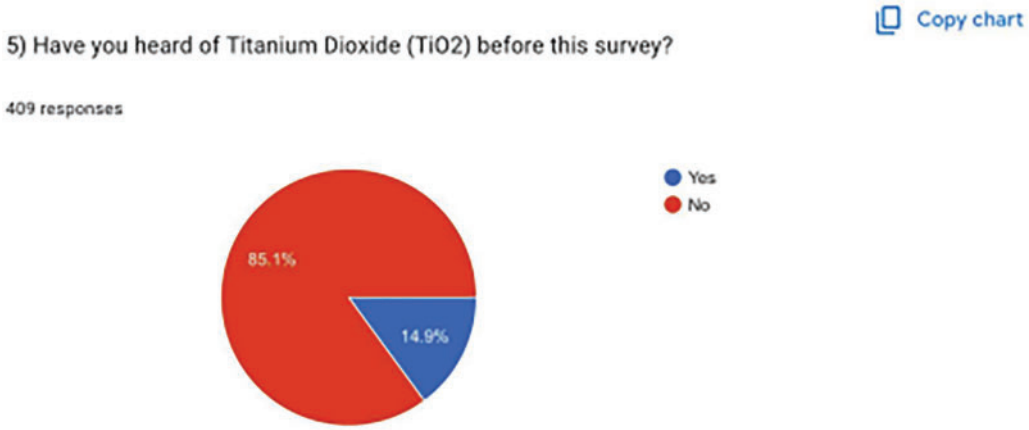

Figure 6. Response to Question 5 in the First Survey: "Have you heard of Titanium Dioxide (TiO_2) before this survey?"

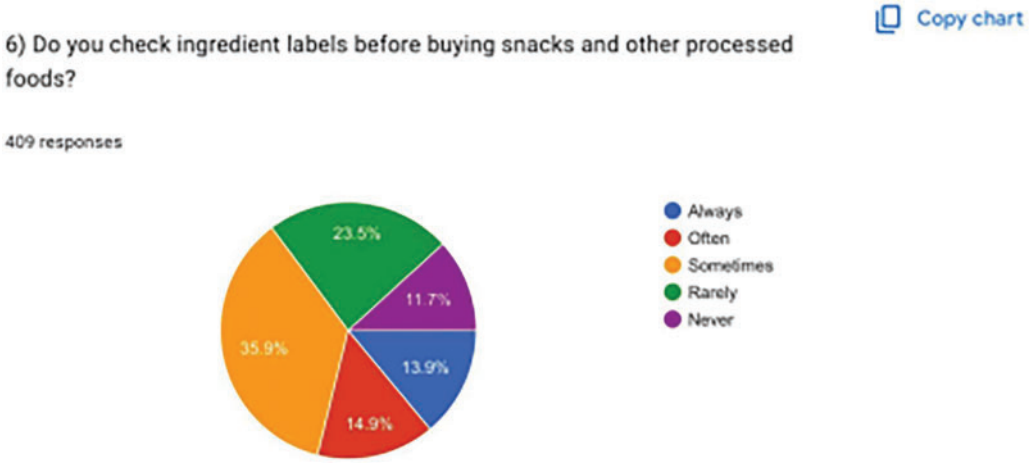

Figure 7. Response to Question 6 in the First Survey: "Do you check ingredient labels before buying snacks and other processed food?"

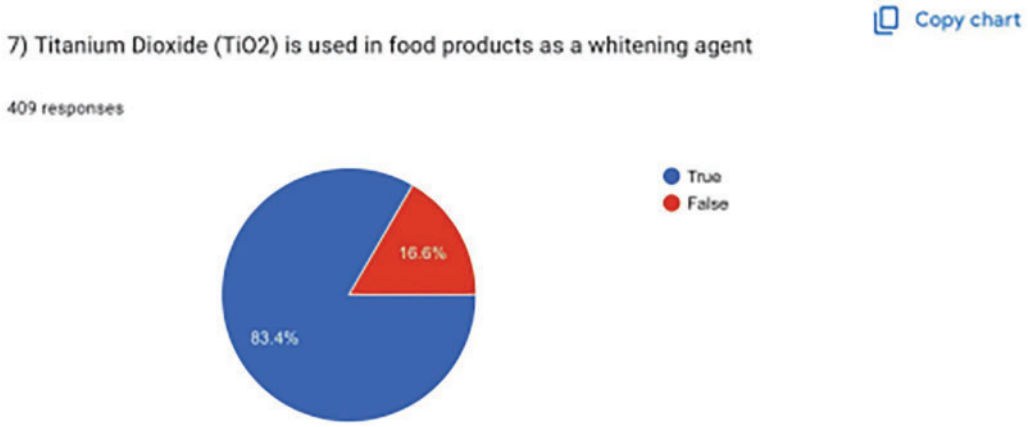

Figure 8. Response to Question 7 in the First Survey: "Titanium Dioxide (TiO_2) is used in food products as a whitening agent?"

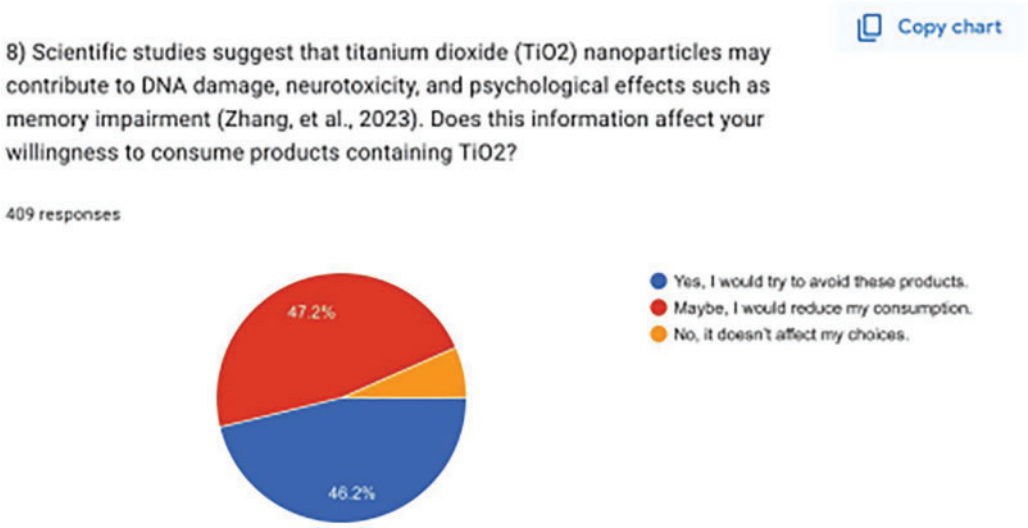

Figure 9. Response to Question 8 in the First Survey: "Scientific studies suggest that titanium dioxide (TiO_2) nanoparticles may contribute to DNA damage, neurotoxicity, and psychological effects such as memory impairment. Does this information affect your willingness to consume products containing TiO_2?"

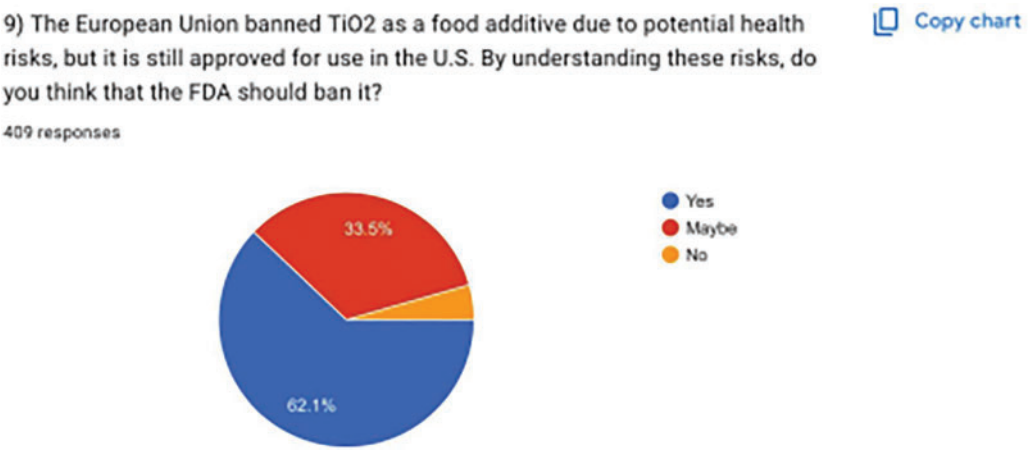

Figure 10. Response to Question 9 in the First Survey: "European Union banned TiO_2 as a food additive due to potential health risks, but it is still approved for use in U.S. By understanding these risks, do you think FDA should ban it?"

Appendix B: Response to Questions in the Second Survey

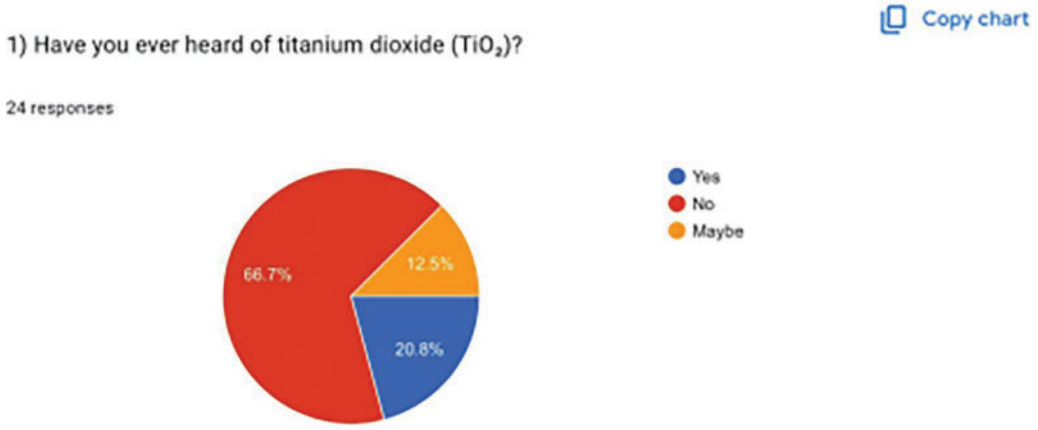

Figure 11. Response to Question 1 in the Second Survey: "Have you ever heard of titanium dioxide (TiO_2)?"

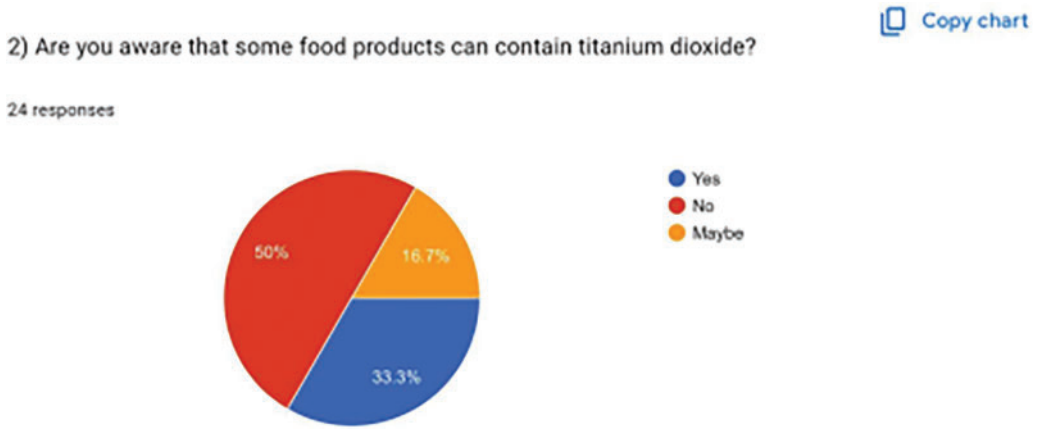

Figure 12. Response to Question 2 in the Second Survey: "Are you aware that some food products can contain Titanium dioxide (TiO_2)?"

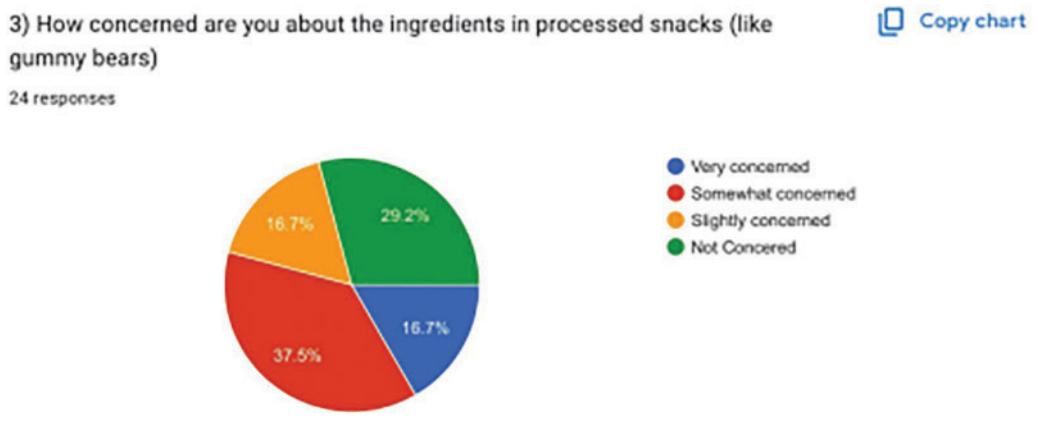

Figure 13. Response to Question 3 in the Second Survey: "How concerned are you about the ingredients in processed snacks (like gummy bears)?"

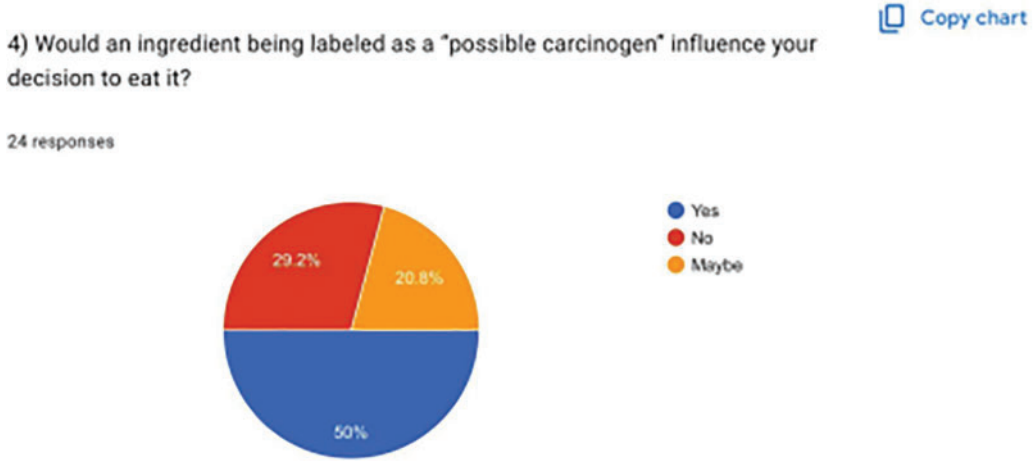

Figure 14. Response to Question 4 in the Second Survey: "Would an ingredient being labeled as a "possible carcinogen" influence your decision to eat it?"

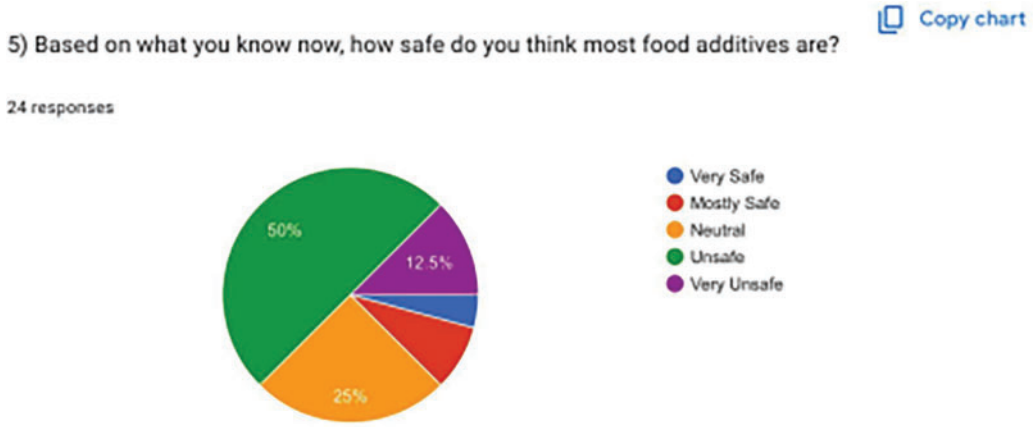

Figure 15. Response to Question 5 in the Second Survey: "Based on what you know now, how safe do you think most food additives are?"

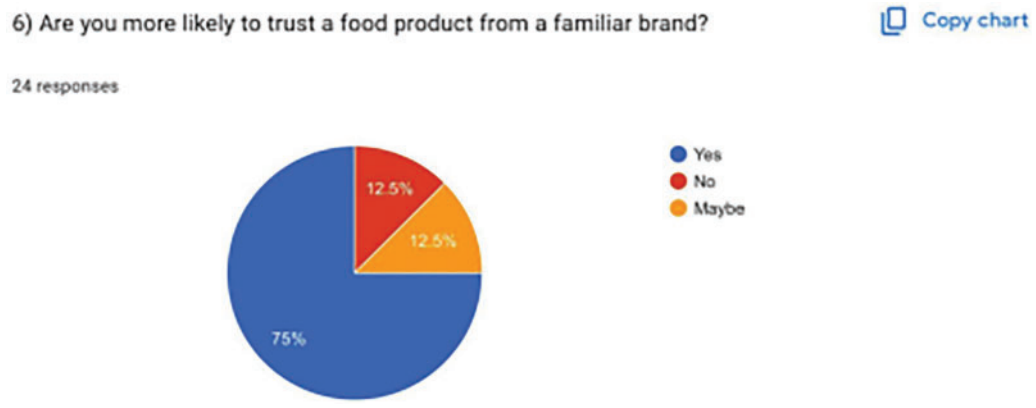

Figure 16. Response to Question 6 in the Second Survey: "Are you more likely to trust a food product from a familiar brand?"