Executive Review of the Stevia Food System

Plan B Project

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Prologue

In my first few years at the University of Minnesota, food science was my major and I had a career goal of potentially working in Research and Development at General Mills. I was fascinated by the possibilities of changing the food system from within the food itself. As time progressed, I took more of my classes for my second major, nutrition, and found that I also loved the biology and bodily sciences that took place around food after it was ingested into the body. The more I learned about nutrition, the more I realized I liked it more than the chemistry of food science and saw my future more prominently in this field. I have always wanted to help people as the basis of my career, so I found that within this area of expertise I could possibly reform policy, do research directly related to the public. After graduating with my undergraduate degree in nutrition with a minor in food science, I decided to go back to school for another year to round out my nutrition education. In obtaining my master's in nutrition, a potential project emerged about a systems review of stevia. It sounded incredibly interesting to me and I was happy to take on the challenge. This review slowly turned into a call to action after discovering that the public's sugar intake and obesity challenges were higher than originally anticipated. Our nation faces a growing obesity epidemic with no end in sight. Analyzing how the food system must change in order to solve this issue resulted in stevia sugar-substitution being a potential approach to managing the problem. In order for stevia to find success, four main changes must occur within the food system, each change is analyzed in detail within the following work. In the future, this paper serves as an example of what problem-solving can bring if the system is carefully analyzed . It also serves as a template for how to bring alternative sweeteners like stevia to become more prominent in the market. I have hopes of publishing this work so more people in the field can learn about stevia through the use of a systems approach as I have done over this past year.

Abstract

Stevia is an alternative sweetener that provides sweetness to foods without the caloric value of traditional sweeteners such as sucrose. With the rise of an obesity epidemic in the United States, industry is faced with increased pressure to make products with fewer calories, yet with the same or similar palatability as the original product. Alternative sweeteners such as stevia are used to add sweetness without adding calories since the body cannot use the stevia molecule for energy. The gradual introduction of these alternative sweeteners within the American food system could contribute toward greater availability of foods with less caloric density. To increase the feasibility of gradually incorporating alternative sweeteners into common foods traditionally made with sugar ingredients, this paper focuses on four main pillars within the Stevia food system: decreasing the cost of scaling production, improving product formulation, addressing flavor modification, and maintaining consumer acceptability. These four fundamental basic food system functions serve as a guide for scaling-up and gradually introducing non-caloric sweeteners as viable ingredients in traditionally sweetened food products. Addressing our pressing public health issues necessitates a gradual substitution with alternative sweeteners such as stevia. This gradual introduction requires a food systems approach addressing the barriers, challenges and opportunities within our food system while balancing consumer needs, wants, and desires.

Introduction

Over the past 50 years, the incidence of obesity, diabetes, and cardiovascular disease continues to rise, which is associated with overconsumption of calories and increased added sugar in foods. Studies suggest increased added sugar and calorie consumption costs the United States billions of dollars in healthcare-related expenses. As a public health approach, sugar is being replaced with alternative low- and non-caloric sweeteners. Stevia is gaining prominence as a natural alternative sweetener. The replacement of added sugar with stevia, even in small amounts, has the potential to decrease overconsumption of added sugar. Finding solutions to the systemic challenges of scaled production costs, flavor modification, product formulation, and consumer acceptance can position stevia for market success. This paper provides background on the history of stevia and gives an overview of the public health and economic impacts of added sugar consumption. Then the paper discusses the health implications of stevia consumption. The paper provides an overview of the critical challenges facing scaled stevia production and product formulation, from farm to fork. Finally, the paper provides recommendations meant to ease production and adoption of stevia-sweetened products based on a food systems framework.

Background

Plant Characterization

The *Stevia* genus is part of the Asteraceae family, commonly called the sunflower family. The *Stevia* genus includes more than 200 species, yet only ~20 of these species are cultivated for commercial production. *Stevia rebaudiana* Bertoni (stevia, hereafter) is the most commercially relevant species used in sweetener production due to the high presence of sweet steviol glycoside compounds produced in the leaves. There are more than 40 different steviol glycosides, with the most relevant being Rebaudioside (Reb) A, Reb D, Reb M, and stevioside. Each glycoside confers unique flavor characteristics, and these glycosides have been extensively characterized through analytical chemistry and sensory science.[1]

The stevia plant is native to the Rio Monday Valley in Paraguay where it grows in sandy soils next to streams. The plant grows best in 25ºC tropical climates with at least 1375 mm of rain year round.[2] Under these conditions, the plant can grow up to 1-2 feet in width and height with green leaves less than 1 inch in width and length arranged opposite each other on the main stem. Stevia grows tubular purple or white flowers with 4-5 petals.[3] Since stevia is self-incompatible, the plant requires cross pollination, which is often carried out using bees or flies in commercial production programs. Stevia seeds are achenes covered by a feathery pappus. Fertile seeds are dark while infertile seeds are clear or yellow. They have very little endosperm and are dispersed by the wind.[2]

Steviol glycosides accumulate in the leaves as the plant matures. Glycoside synthesis slows prior to or during flower production. Longer daylight periods influence the duration of plant growth before flowering, allowing the plant to develop higher quality leaves. For example, one study showed plants receiving 11 hours of daylight flowered after 46 days while plants receiving 12.5 hours of light flowered at 96 days. When given 16 hours of daylight, the plant remains in a vegetative state and continues to increase in biomass.[2] Thus, to achieve the sweetest and highest quality leaves, trimming the flowers or buds allows for optimal sun exposure and increased steviol glycoside production.

Historical Timeline of Stevia Use

Stevia has a rich history, dating back over 200 years. Before the 1800s, Ka'a he'e or "sweet herb" was used widely by the Guarani Natives in Paraguay. Uses of stevia included chewing leaves for pleasure, sweetening teas, and medicinal purposes.[4] Utilization of stevia leaves for medicine was identified as an early form of blood sugar management for the Guarani people.[5(p7)] By the 1800s, use of the herb as a natural sweetener spread across regions of Brazil and Argentina. In the late 1800's, Dr. Moises Santiago Bertoni, the College Director of the Asuncion School of Agriculture in Paraguay, first learned about the stevia plant from local native guides and wanted to characterize it for research purposes. Eventually Bertoni received a packet of stevia leaf fragments which served as tangible evidence for the scientific characterization and discovery of stevia. By 1903, a live plant was collected and studied at the college.[1] A few years later, the plant was officially named *Stevia rebaudiana* Bertoni, reflecting the efforts of Dr. Moises Santiago Bertoni, and the chemist working with Bertoni, Ovidio Rebaudi.[6]

Stevia garnered broader commercial interest during the early 1900s. In 1918, Stevia became known to the United States Department of Agriculture (USDA) by an American Trade Commissioner, George Brady, who recognized it as a "new sugar plant with great commercial possibilities".[4] In 1931, two French chemists isolated a pure crystalline compound which gave stevia leaves its sweetness, steviol glycosides. These glycosides were found to be 50-450 times sweeter than sucrose.[7] However, an American government researcher, Dr. Hewitt G. Fletcher deemed stevia of no benefit to the American industry, citing stevioside as "not being useful".[4] By 1970, Japan began commercializing products containing refined stevioside.[4] From 1988 to 1994, 41% of Japan's food market of potently sweet substances contained stevia, and stevia gained popularity as a tabletop sweetener.[4]

In 1991, the United States dubbed stevia as being potentially carcinogenic and an "unsafe food import" by the FDA.[8] This claim was due to conflicting reports which found raw stevia and unrefined extracts could negatively affect fertility.[8] Without approval for food use, stevia plants and extracts were not allowed into the United States.[9] However, the 1991 claims were repudiated by a follow-up study in 1995, and stevia was regulated as a dietary supplement.[8] In the early 2000s, patents for stevia products expired in Japan, which allowed Chinese manufacturers to make more products at a lower cost. At the same time, major US food companies such as Coca-Cola and Cargill pushed for stevia approval by patenting the use of Reb A in their products. As more studies had been conducted since the 1990s disproving the poor health effects of stevia, Reb A became Generally Recognized as Safe (GRAS) in 2008.[9] Truvia, a popular tabletop product, was one of the first widely available stevia sweeteners launched in 2008 by Cargill.[10] Since 2009, many new products and manufacturing techniques have been developed for stevia products, and more research has been done to make stevia more palatable and cost-effective.

Regulatory Timeline

Currently, over 150 countries have approved stevia for use, as seen in Figure 1.[11] Japan first approved stevia for use in the 1970s. In 1975, the first modern test of stevia was conducted using a mouse model to evaluate the safety of short term and long term use, as well as during pregnancy. No

Figure 1: World Map of Stevia-Approved Countries[11] (permission requested)

adverse events were reported in regards to short and long term health and for reproductive purposes.[12] From 1975 to 1995, the FDA received many petitions and demands for stevia to be approved as a food additive, but there was insufficient evidence at the time to support commercial use.[13] In 1991, the importation of stevia was banned by the FDA when they issued Import Alert #45-06: "Detention without Physical Examination of Stevia Leaves, Crude Extracts of Stevia Leaves and foods containing stevia leaves and/or Stevia Extracts".[14] This designated any imported stevia sweetener, leaves, or extracts subject to detention. In 1995, the Import Alert was revised to exclude dietary supplemental stevia products after stevia was only approved as a supplement by the FDA.[15] In 2008, stevia finally received GRAS status for the use of Reb A. Two years later, the FDA revised the same import alert to account for the Joint FAO/WHO Expert Committee on Food Additives (JECFA) regulatory definition, stating that only steviol glycosides that were 95% pure, or going to be further processed to 95% purity were allowed after inspection.[16] The European Food Safety Authority (EFSA) also approved the use of stevia in food in Europe around the same time.[13] More recently, the Import Alert was revised to exclude many more GRAS steviol glycosides and revise technical languages on the document to be more specific for the United States.[14]

GRAS Status in 2008

For the FDA to consider stevia safe to consume and for use in products, they must consider chemistry, toxicology, and microbiological safety. Chemistry "addresses the substance identity (the scientific name, composition, and source), intended use and technical effect, estimated dietary exposure, sweetness intensity relative to sucrose, method of manufacture, and specifications for composition and potential contaminants."[17] Stevia extracts must reach a minimum threshold of 95% pure steviol glycosides before they reach market. This threshold was set by the JECFA in the mid 2000s and has since been adopted by CODEX. Therefore, stevia extracts are commonly referred to as SG95 extracts in the commercial setting. Products reaching this purity threshold are manufactured using three processes which will be further addressed later in the review: extraction and purification directly from the plant leaves, enzymatic bioconversion of purified extracts, and biosynthesis using genetically engineered microorganisms.[17]

Toxicology evaluates studies related to stevia used as intended (i.e., as a sweetener) and identifies safe levels of dietary exposure, safety data, and enzymes used.[17] Dietary exposure data are based on estimates where sucrose is substituted by steviol glycosides for different populations in different areas in the world and are expressed as steviol equivalents.[17] This information is compared against the Acceptable Daily Intake (ADI), which was established by JECFA to be 4 mg/kg/day.[18] The ADI is the amount of a substance an individual can consume on a daily basis over the course of an entire lifetime without experiencing negative health outcomes. Many studies have exhibited little or no toxicity when stevia was consumed.[19] The ADI plays an important role in product formulation as it informs safe usage levels in product development. Finally, microbiological assessments address the use of enzymatic modification of bacteria to produce steviol glycosides.[17] This is the most recently approved production method and is becoming more relevant as companies use fermentation processes to produce steviol glycosides. Overall, these considerations helped stevia achieve GRAS status in 2008, which allowed stevia to be openly used in a wider variety of foods, food products, and beverages. Since 2008, more than 40 different stevia ingredients have achieved GRAS status.

Consumer and Societal Health Benefit

Sugar and It's Public Health Impact

Added sugars are ubiquitous in the diet and chronically over consumed, often unknowingly. The FDA defines added sugars as "sugars that are added during the processing of foods" [20] and includes "sucrose, dextrose, table sugar, syrups, honey, and sugars from concentrated fruit or vegetable juices".[21] The average consumer eats 17 teaspoons of added sugar per day, equivalent to more than 50 pounds per year. Added sugar alone contributes 266 kcals/day to the average American diet. Sugar-sweetened beverages (SSBs) are the most common source of added sugar in the diet, with 24% of the top sources of added sugar coming from SSBs.[22(p43)] Other common sources of added sugar include baked goods, confections, packaged snacks, sauces, and condiments.

Dietary guidance and product labeling initiatives aim to curb added sugar consumption. The 2020-2025 Dietary Guidelines for Americans recommends limiting consumption of added sugars to less than 10% of dietary calories. In 2016, the FDA implemented new requirements for the Nutrition Facts Panel (NFP), stipulating that Added Sugar must be labeled on the NFP along with their contribution to daily caloric load, with a Daily Value set at less than 10% of caloric intake.[20] Now that added sugar is listed on the NFP, some food manufacturers are working to decrease the sugar content in foods while keeping the same amount of sweetness. Product formulators are turning to alternative sweeteners to decrease sugar content while maintaining the sweetness that consumers expect. Stevia has gained prominence as a label-friendly natural alternative sweetener. Substituting added sugars with stevia has the potential to decrease the burden that added sugars place on US public health.

Added sugar consumption negatively influences public health and economic outcomes. Increased added sugar and calorie consumption contribute to an increased risk of obesity, diabetes, and cardiovascular diseases.[21] According to the CDC, these diseases play a huge role in Americans' daily lives since one in three adults and one in five children struggle with obesity. Having obesity also increases risk for developing cardiovascular diseases and diabetes, so lowering obesity can eventually decrease the risk of these diseases. Obesity costs the US healthcare system $173 billion annually.[23] The average American who is obese pays around $1,821 more in medical bills than someone who is at a healthy weight.[24] Heart disease is the leading cause of death in the US, accounting for 1 in 5 deaths.[25] Heart disease costs more than $220 billion annually. Meanwhile, more than 30 million US adults live with diabetes while another 96 million live with prediabetes.[26] Diabetes costs the US over $320 billion annually.[27] All together, added sugar consumption is associated with some of the most deadly chronic diseases, which have a tremendous public health and economic impact.

Reducing added sugar consumption by reformulating products with natural sweeteners like stevia has potential to reduce negative public health and economic outcomes. A 2021 Tufts University microsimulation study found that decreasing added sugars by only 20% and 40% in sugar-sweetened beverages would prevent 2.48 million cardiovascular events and save 0.75 million people from diabetes.[28] Additionally, it would collectively save $160.88 billion in healthcare and personal costs over a person's lifetime.[28] The study was based around the US National Salt and Sugar Reduction Initiative (NSSRI), which aims to reduce the number of diet related diseases in the United States through a "partnership of organizations and health authorities across the country".[29] The microsimulation model used was Cardiovascular Disease Policy Model for Risk, Events, Detection, Interventions, Cost, and Trends (CVD-RISK).[28] The model utilized the probability of individual risk factors for CVD, diabetes, and estimated costs of treatment in conjunction with National Health and Nutrition Examination Survey (NHANES) data that contained 24-hour recalls, demographic data, and sugar consumption from 2011 through 2016. Based on both data sets, the model created a population and reduced mean sugar consumption by 20% and sugar-sweetened beverages by 40% and followed the mock-population for ten years and for life. The results suggest that even with a small amount of sugar reduction, 515,000 CVD events were averted within 10 years and $27.29 billion were saved in formal healthcare costs alone, as seen in Table 1. Given the option of the food and beverage industry adopting these changes over a period of time, many lives and dollars could be saved.

	10 years	**Lifetime**
Population, million	163.18	163.18
Average simulated follow-up years per person	9.40	28.33
Reduction in added sugar intake per person, g/d, n (%)		
From SSBs	4.1 (22.9)	6.3 (34.0)
From foods	2.5 (11.0)	3.7 (17.0)
Cases averted, thousand, n (%)		
CVD events	515 (2.5)	2,483 (2.7)
CVD deaths	68 (1.5)	490 (1.7)
Diabetes mellitus cases, n (%)	209 (0.8)	750 (2.0)
QALYs gained, million, n (%)	0.33 (0.02)	6.67 (0.2)
Change in policy costs, $, billion		
Government implementation costs	0.002	0.002
Government monitoring and evaluation costs	0.003	0.003
Industry reformulation costs	23.01	23.01
Change in health-related costs, $, billion		
Formal health care costs	-27.29	-141.05
Informal care costs	-0.03	-0.08
Productivity costs	-4.73	-42.75
Net costs, $ billion		
Health care perspective	-4.28	-118.04
Societal perspective	-9.04	-160.88
ICER, $/QALY		
Health care perspective	Cost-saving	Cost-saving
Societal perspective	Cost-saving	Cost-saving

Table 1: Health Gains, Costs, and Cost-Effectiveness of the National Salt and Sugar Reduction Initiative Voluntary Sugar Reformulation Policy Among US Adults at 10 years and Lifetime from Societal and Health Care Perspectives[29] (Permission Requested)

Mounting evidence including the CVD-RISK study[28] and public health initiatives including the National Salt and Sugar Reduction Initiative (NSSRI)[29] both support a reduction in sugar consumption. Necessitating the development, application, distribution, and marketing of viable alternative ingredients to meet consumer desires for sweetness within the context of cost, health, and environmental impact. A holistic, integrated, and continuous initiative, based upon cooperation within the food system, as to the roles, functions, and activities, which allows a transitory period for gradual introduction of alternative ingredients is paramount. As supported by the White House Conference on Hunger, Nutrition, and Health (October 2022) this transitory period requires that *"Everyone has an important role to play in addressing these challenges: local, State, territory and Tribal governments; Congress; the private sector; civil society; agricultural workers; philanthropists; academics; and of course, the Federal Government."*[30]

Incorporating stevia ingredients into commonly consumed foods traditionally made with sucrose will require focused attention concerning four main functions in the stevia food system: decreasing the cost of scaled production, refining formulation, improving taste, and emphasizing the consumer and societal health benefit. By addressing the barriers, challenges, and opportunities within each of these food system functions we can address why, how and what needs to be addressed to allow stevia to become an integral part of the solution. By scaling stevia manufacturing in a manner which is attainable and efficient for the growing demand of stevia, the cost of production can decrease and result in more profit for industry. In addition, revising formulations will likely improve workability of stevia in products, making it more appealing to manufacturers and product developers to use the ingredient. Also, creating a product with a flavor more equivalent to sugar will improve consumer perception of stevia and generate a more favorable attitude towards use of stevia in familiar products. Finally, accentuating the importance of many health benefits stevia substitution contributes to consumers will encourage society to allow welcomed change to take effect within their food system and food environment. Ultimately, stevia will require a foundational model based on a systems approach involving sectors, disciplines, and cultures working together to manage macro and micro barriers, challenges, and opportunities through targeted consumer experiences. This approach is an initial evaluation / assessment / examination of four key functional steps in a systematic process that allows stevia to transition as a more common ingredient into the American food supply.

Stevia: a Non-Caloric and Diabetic-Friendly Sweetener

Stevia products, labeled as stevia, stevia leaf extract, or steviol glycosides serve as popular non caloric sweeteners. These products derive their sweetness from steviol glycosides, as seen in Figure 2, present in the stevia leaves. These products lack caloric value because the steviol backbone on the steviol glycoside molecule is indigestible to humans. Sugar units surround the steviol backbone, and these molecules trigger the sweet taste receptor on the tongue. Steviol glycosides are commonly 200+ times sweeter than sucrose.[31]

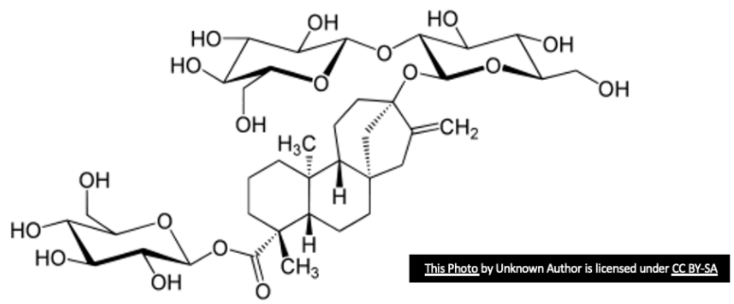

Figure 2: The chemical structure of a steviol glycoside.

Since steviol glycosides are not metabolized, they lack negative consequences associated with sugar, like increased weight gain, increased glycemic load, and insulin insensitivity. A study conducted by Higgins and Mattes in 2019 compared sucrose to four low or non-caloric sweeteners consumed by more than 100 overweight individuals in a randomized control trial. Participants were assigned to drinking 1.25-1.175 L of beverage daily, each sweetened with either sucrose, rebaudioside A (stevia), aspartame, saccharine, or sucrose. After 12 weeks, the participants who drank the sucrose or saccharin-sweetened beverage had gained about 1.5 pounds more than those who consumed the other sweetened beverages.[32] Since stevia does not affect insulin levels, lipid levels, HbA1c, or blood glucose, this natural sweetener serves as an alternative for diabetics because it does not elicit the negative consequences of sucrose.[33]

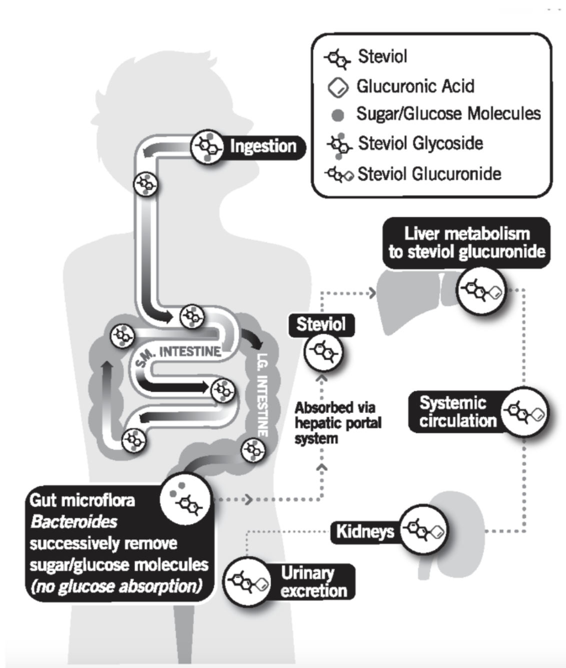

Figure 3: Metabolism of Stevia in the Human Body[32] (permission requested)

Stevia does not have the same metabolic function as sucrose because steviol glycosides are not absorbed by the body when ingested. Once stevia is consumed, the glycosides pass through the stomach and intestines fully intact until they arrive at the large intestine, as seen in Figure 3. In the large intestine, bacteria in the microbiome remove the sugar units, which leaves only the steviol backbone. Finally, the steviol backbone is absorbed into the bloodstream with liquids in the colon. Once steviol arrives at the liver it is modified to steviol glucuronide and then shortly after excreted in the urine.[31]

Stevia and the Microbiome

Large intestine bacterial metabolism of stevia has raised concern over potential negative effects of microbiome disruption. The literature reports inconclusive results, with stevia consumption by human adults and rat models resulting in neutral effects on the microbiome, while stevia consumption by maternal dams and offspring resulting in more negative or neutral effects.

An article published in 2019 by Netteleton et. al., used rats to compare the effect of stevia on the short chain fatty acids (SCFAs) produced by the microbiota present in the gut.[34] The groups receiving stevia showed no different alpha and beta diversity among the microbiomes but increased their acetate and valerate SCFA production in the colon. Increased SCFA production improves blood pressure regulation, lipid metabolism mechanisms, and anti-inflammatory responses.[35] Another article from 2020 studied the effects of stevia on murine models using four different treatment groups of rats comparing stevia and saccharin on a high fat diet with two control groups.[36] The results identified the most prominent of the microbiota species present in the fecal samples, Firmicutes and Bacteroidetes. The ratio between these two bacteria was changed by the different sweeteners, suggesting an altered ratio leads to altered gut microbiota homeostasis, a negative effect with ties to obesity or other adverse colonic events such as inflammatory bowel disease.[37] Finally, an external study conducted with humans suggested a neutral effect on SCFA production in the microbiome. Thirteen volunteers donated fecal samples, which were fermented in batch cultures using fecal slurries with fiber substrates made of apple pectin, cellulose, raftilose, cellose, and maize starch. They were incubated with 50% of the acceptable intake of stevia. Results showed stevia produced no effect on the production of SCFAs and there were no alterations in OTUs, a neutral effect.[38]

Stevia given to obese, pregnant maternal dams may negatively affect the microbiome of the offspring. A study published in 2020 by Nettleton et al. evaluated the effect on obese impregnated dams fed stevia during gestation and on the offspring's microbiotic environment.[39] The results showed the stevia-fed dams' offspring exhibited increased body fat percentage in both sexes and a larger body weight in the transplanted microbiome offspring, a negative effect. Another study by de la Garza et al. in 2021 used a similar approach as Nettleton et al. 2020 to examine the effect of stevia in combination with a high fat diet on pregnant dams, except the high fat diet fed before pregnancy was a Western diet containing high fat human foods like chocolate and fried potatoes.[40] Once pregnant, the dams were fed either sucrose via condensed milk, honey, or stevia with their standard diet and offspring were fed the standard diet after weaning. As a result, *Lactobacillales* was higher in the stevia group when compared to the control. *Lactobacillales* is usually elevated in the microbiome for obese individuals, which could explain the alterations seen in the results since the mothers were obese.[41] Finally, the last article from 2022 by Tsan et. al. studied the effect of stevia given in water bottles of two groups of very young males and females.[42] Consuming stevia at a young age proved to have no effect on the microbiome of the very young rats as PERMANOVA and Shannon diversity showed no significant difference between the microbiome of rats that consumed stevia and those that did not.

Scaled Production and Cost

Farming Requirements

Stevia has been cultivated for over 200 years, yet farming practices are being optimized for commercial production. To ensure optimal growth, stevia requires a rich and sandy soil that is well drained and slightly acidic with a pH anywhere from 6-7.5.[43] While growing stevia from seeds is possible, clonal propagation is the most relevant commercial production system. Cuttings taken from stock plants are transplanted into commercial fields using traditional vegetable transplanters. Lower leaf cuttings should be taken with 4-6 nodes and planted in the soil. About 10-15 days later, roots should appear. Then, the cuttings are transplanted into a soil sleeve.[44]

After about 50-60 days in the soil sleeve, the seedlings or cuttings are transplanted to the field or raised bed. Proper irrigation and drainage are important because stevia cannot tolerate water logging or drought during the hot summer months. Since stevia does not grow quickly after first being transplanted, weeds must be managed frequently, with mulching serving as an effective weed control system.. Caterpillars are common pests in the early life of the stevia plant. Diseases like leaf blight and leaf spot are also common and have great potential to decrease leaf yield. During rainy seasons, without proper drainage or water control, stevia is prone to root rot which could ultimately kill the plant.[44] A drip irrigation systems maintain the proper moisture content in the soil and can potentially prevent root rot, leaf blight, and leaf spot, making it a wise investment for farmers.[45] Flower buds should be clipped to continue steviol glycoside development if needed, otherwise harvest should be initiated right before flowering.[46] Depending on location of production and the year of planting, stevia is usually ready to harvest around 60-90 days after transplantation and has a productive life cycle of 3-5 years, being harvested 2-3 times per year.[47]

Stevia Leaf Harvest and Drying

Stevia leaves can be harvested using repurposed conventional vegetable harvesters. Once plants are harvested, they are dried to prevent potential loss of steviol glycosides and leaf browning. Drying the leaves to about 10% moisture from the original 80% after harvest preserves the leaves and also prevents mold growth during storage and shipping. Plus, shipping dried leaves is less expensive when taking into account the cost of 22 kg of dried leaves vs. the 100 kg of freshly harvested leaves.[48]

There are many types of drying methods such as sun drying, solar tunnel drying, modified flatbed drying, and a series of industrial dryers. First, sun drying is a traditional method for drying leaves. A basic approach is to place a plastic sheet in the sun and distribute stevia leaves in a thin layer. The leaves are turned and rotated with rakes often. Black plastic sheets are preferred because it increases the temperature and evaporation rate due to the color's greater solar absorption. Another sun drying approach uses plastic mesh screens to hold the stevia above the ground on a bamboo table structure about a foot and a half off the ground. This gives the leaves exposure from the top and bottom which will dry the leaves faster and more uniformly. Sun drying usually takes about 9-10 hours in a lower humidity climate. It is not advised to dry the leaves out in the open in tropical conditions or climates because extreme solar radiation can damage the leaves. To help this, shade nets placed above the leaves create partial shade while still continuing to dry the leaves with the heat of the air.[48]

Solar tunnel drying is another method to dry stevia leaves. Similar to greenhouses, solar tunnels contain plastic or mesh siding with cement floors painted black to increase solar radiation absorption. Chimneys are placed at the top to allow for hot, humid air to escape for more effective leaf drying. Between the outside and inside of the solar tunnel, there is a 10-15ºC (50-50ºF) differential. The tunnel can maximize the space by using a shelf system inside and at the same time keep the leaves clean without the outside contamination of airborne dust.[48]

Modified flatbed dryers, which were traditionally used for drying coffee and cereal, are another method used for drying stevia leaves. This equipment is a box made of wood, bricks, concrete, or metal sheets with an open top and a false bottom made of mesh for the stevia to sit on. Hot air is blown beneath the leaves and humid air flows out the top as the leaves dry. This makes for faster, more efficient indoor drying which cannot be influenced by the elements. However, this model is more expensive than sun drying or solar drying with considerable initial expenses for the dryer, the continual cost of gas to power the machine, plus maintenance as needed.[48]

Though initially expensive, investments in industrial drying machines may offer downstream cost savings through decreased labor and drying consistency and enhanced efficiency. Industrial dryers include microwave dryers, tray dryers, mesh belt dryers, and tobacco barns. Using a microwave dryer, stevia leaves pass through a conveyor belt heating the leaves by microwaves to the boiling point, where the water evaporates and exits the machine through air blowers. This machine is computer operated, controlling the belt speed, microwaves, temperature, and air flow. This makes it less prone to human error which can help save on costs. Another option is the tray dryer, where leaves are placed on racks and the entire dryer is rolled into a chamber. The chamber is heated by an air heater as hot air circulates through, drying the stevia leaves in the process. Computers control the temperature of the chamber using a thermostat, which also saves on costs related to human error. Finally, there is the belt mesh dryer, which is likely the gold standard for stevia leaf processing and is the most gentle method of drying. The perforated belt carries the leaves through many sections for drying, each can be regulated to their own temperature and controlled with air exchangers. The speed of the belt is controlled, which makes for a more unique drying process. Air is passed through the stevia leaves until they have the preferred vapor content, or is dry. Additionally, tobacco drying barns are being adapted as an affordable drying method in the southern US.[49] This serves as an economical option to repurpose equipment and increase sustainability of stevia production. There are many methods to dry stevia leaves, each option being unique to the processor's preferences and needs.[48]

Preparation for Shipping

After the leaves are dried, the stems are separated from the leaves because they contain tannins and waxes that could negatively affect the purification process during the glycoside extraction step. Some processors may choose to remove the stems either before or after drying using several methods. First, the mini defoliator is popular on Chinese farms. This machine is a small rubber horizontal cylinder that rotates above a metal chute. The stevia leaves can be held against the rolling cylinder, which strips the leaves from the stem. There is a low power requirement for this method and the machine is relatively small, but this can be a tedious and laborious process. Other producers use a continuous leaf-stem separator. Here, the leaves are separated using a rotating drum and airflow after being fed through a tunnel. Finally, there is a winnowing separator that uses vibratory movement to separate the stems from the leaves. This method doesn't work on wet leaves, so this must be used after drying.[48]

After leaf-stem separation, a horizontal baling and bagging machine packs stevia leaves into compact bricks as the final step before shipping. The machine has two arms, one for compressing the dried leaves into bales and the other to push the bale into a bag. After this, it can be stored, but is usually shipped to manufacturers for steviol glycoside extraction.[48]

Steviol Glycoside Leaf Extraction

Once the bales arrive at the processing plant, the steviol glycosides are extracted from the leaves. First, the dried leaves steep in a hot water bath. After steeping, the leaves are removed and the leftover liquid is purified over a few steps. The liquid is then passed through an ion exchange chromatograph where the electrical charge of the steviol glycosides are captured and trapped like a sieve. Non steviol glycosides are considered waste and flushed away. The electrical charge holds the glycosides in place, and a pure alcohol rinse releases them. Now, the alcohol must be removed. The majority of the glycosides are removed by a membrane filter while leftover compounds are later purified by distillation. Now that a yellow syrup remains, the color needs to be removed. The syrup is passed through activated carbon, and then smaller residual particles are removed by pressing it through a filter. Lastly, the solution is sprayed into a tank filled with hot air. The fine droplets meet the air, which evaporates the very last of the water and turns the steviol glycosides into crystals. This step produces the primary extract, which tastes very bitter and metallic with the varying amounts of different types of steviol glycosides. The most commercially relevant steviol glycosides are Rebaudiosides A, D, and M, and they each impart unique flavor characteristics. Each batch has varying amounts of steviol glycosides and is dependent on the amount of heat and sun obtained by the plant during growth. Due to the varying levels of steviol glycosides in the final product, the batch may be more refined before use in food and beverage manufacturing.[50]

Refining the Primary Extract

Repeated crystallization further purifies and separates steviol glycosides. The stevia extract is dissolved in alcohol and heated to evaporate. The vapor is put through a distillation column, a tube or tower which cools the solution enough to form crystals.

After the first time, stevioside crystals are formed, filtered off, and put aside. Another round of dissolving, heating, evaporation, and crystallization is done and Rebaudioside A is formed, filtered off, and set aside. This process can be repeated several times to obtain other rebaudiosides. However, with each additional refinement process, the more expensive the end product will be. Purification of individual rebaudiosides can be achieved through subsequent refinement processes, resulting in high purity single rebaudioside extracts. Continuous refinement of single rebaudioside extracts tends to be costly, especially for steviol glycosides occuring at low volumes in the plant, like rebaudioside M.[50]

Mixing and Packaging the Rebaudiosides

In the conventional system, individual steviol glycosides are blended to achieve an ingredient specification desired by product formulators. For example, a solution with 99% pure Rebaudioside A may be mixed with a 50% pure Rebaudioside A to reach a desired purity specification. In this case, there may also be other steviol glycosides (e.g., Reb D or Reb M) in the extract. Blending gives each stevia product unique flavor characteristics. Also, blending allows for consistent quality in the product and the formula. This aspect is important for labeling and quality control, which is highly regulated by the FDA.[50]

Fermentation-based Steviol Glycosides

Fermentation is another alternative method used to produce steviol glycosides using bioengineered microorganisms, like yeast. This approach has been used primarily to produce Rebaudioside M, which occurs at minimal volumes in the stevia leaf. First, the enzymes involved in the Rebaudioside M biosynthetic pathway are identified within the plant. Then, researchers find and isolate the genes that code for these enzymes. The genes are then copied into expression systems within the yeast to produce the same enzymes involved in the Rebaudioside M biosynthetic pathway. The yeast is fed a glucose syrup made from corn or sugarcane, which converts sugars into Rebaudioside M. Finally, the product undergoes the same extraction process as steviol glycoside syrup from leaves. The resulting extract contains high purity Rebaudioside M. Since Reb M occurs at a rate of 1-2% of the stevia leaf, fermentation provides higher Reb M yield than traditional leaf extracts. However, this process may face hurdles with consumers due to the use of bioengineered microorganisms, and it may be difficult to market this product as natural.[51]

Using Bioconversion to Make Stevia

In addition to fermentation, bioconversion is another method used to make rebaudiosides from steviol glycosides where leaf enzymes are treated with other enzymes. First the enzymes must be produced, yeast strains such as K. phaffii (K. phaffii UGT-b and K. phaffii UGT-b) that express UDP-glucosyltransferase and sucrose synthase are isolated/identified. Some other microorganisms that can be used are *Alkalihalobacillus oshimensis*[52] and *Escherichia coli*.[53] The enzymes from the yeast strains are harvested by centrifugation and held in a buffer solution. They are then passed through a homogenizer to release the enzymes from within the cell by forcing the enzymes to the cell's surface. To make Rebaudioside M, the enzymes are mixed with steviol glycosides and Rebaudioside M is produced over a period of time. Once the enzymes have effectively converted the glycosides into Reb M, the solution is heated to denature the enzymes and then filtered to remove the enzymes. When purifying the rebaudioside solution, the filtered supernatant is poured over macroporous resin in columns, binding to the resin. Then, buffer solutions and food-grade ethanol are used to rinse the columns, and Reb M separates out of the solution. After removal of Reb M, it is chilled to form crystals and fully precipitate from the solution. The crystals are then washed, dissolved in ethanol, and treated with active charcoal to purify the solution. Finally, the solution is recrystallized, dried, and processed to 95% purity.[54]

Stevia Market

In 2021, the stevia market totaled $650 million and by 2030, it is projected to hit $1.6 billion. The Compound Annual Growth Rate (CAGR) of stevia is projected to be 8.9% from 2022-2030 and in the dominant Asia-pacific region, the growth rate will be 10.1% for the same years.[55] Looking at the bigger picture, the United States sugar market was worth $37.62 billion in 2021 and is expected to grow to $46.56 billion by 2029 with a CAGR of 2.72%.[56]

The global sweetener market is highly competitive. The global alternative sweetener market is projected to be worth $7.22 billion and growing at a CAGR of 3.9% by 2029.[57] The alternative sweetener market is segmented into artificial sweeteners, rare sugars, sugar alcohols, and natural sweeteners. Artificial sweeteners include sucralose (e.g., Splenda), aspartame (e.g., NutraSweet), erythritol, and saccharin (e.g., Sweet and Low).[58] Rare sugars occur at extremely low volumes in nature and allulose, for example, is a rare sugar gaining prominence in the market.[59] Allulose is found naturally in figs, raisins, molasses, and maple syrup, but due to its low volume, it is produced primarily by fermentation.[59] Sugar alcohols are also common in processed foods. Some examples include erythritol, mannitol, sorbitol, xylitol, lactitol, isomalt, maltitol and hydrogenated starch hydrolysates (HSH).[60] Sugar alcohols, like erythritol, are commonly produced using fermentation.

As the market grows, some popular stevia products are granulated sweeteners such as Stevia in the Raw, Sweet Leaf, and Truvia. Another popular mode of stevia is in liquid form such as Sweetleaf Sweet Drops.[61] A driving force for market growth is the tax on sugar in some countries and cities. These taxes may push consumers to seek lower sugar options. There is a push to make existing products healthier as consumers become more conscious about what is in their food and what they are putting in their body. For the 72% of Americans looking to lower sugar consumption as of 2021, making the label look more appealing by having less added sugars is a superior route.[62] Finally, diabetics and pre-diabetics (e.g., over 100 million US adults) might prefer the less-chemical taste of stevia compared to sugar alcohols traditionally consumed, since they want to have sweetness without the sugar that contributes to a spike in blood sugar.[55] Table 2 outlines specific marketing considerations for stevia products.

Formulation

Stevia Formulation Challenges

When using stevia in food formulation, certain challenges can occur such as lack of bulk, strange or unappealing mouthfeel, color issues, and structural problems. There is a lack of substance or bulk when sugar is replaced with stevia, especially in baked goods. This is because stevia cannot be used in a 1:1 ratio with sucrose due to the intense sweetness. To add more bulk, low-sweetness intensity carriers such as maltodextrin, are often used in conjunction with stevia. A drawback of this method could be some people may not consider certain bulking agents such as maltodextrin to be clean label, and it may deter people who are buying the product as a health food. Dried glucose syrup and fiber or fiber-like ingredients can also be used instead to achieve a clean label while also effectively adding bulk.[63] Another healthier way to add bulk to products such as Truvia or Splenda, common stevia tabletop sweeteners, is by adding a sugar alcohol like erythritol. Erythritol is metabolized similarly to stevia since it is absorbed in the intestine and excreted without providing any calories.[64]

Another challenge with using stevia in formulation is the lack of freezing point depression and protein denaturation that is usually provided by sucrose. Sucrose usually causes increased protein denaturation and starch gelatinization temperatures while also contributing to the mouthfeel of the product. Sugar also depresses the freezing point of the product, so stevia-containing frozen products, such as ice cream, require additional ingredients in order to achieve the same mouthfeel as a frozen product that contains sucrose. One additional ingredient that can be used is erythritol. This ingredient depresses the freezing point in ice creams, but also provides the benefits of increased bulk and a more-desirable mouthfeel. It also makes it more soft and scoopable compared to using stevia alone in a frozen product.[65]

Browning is another formulation problem that occurs without sugar due to the participation in the Maillard reaction. Allulose can be added to provide brown color since it participates in the Maillard reaction while additionally adding bulk and mouthfeel.[65]

Solubility of stevia when manufacturing beverages is a common challenge. Normally, sugars are made into a syrup that is dissolved in water to add sweetness to liquid products. The ratio of water to syrup is usually around five parts water and one part syrup. However, some rebaudiosides cannot be used to provide sweetness because they are not intense enough to be diluted by water and still have flavor. To fix this, Rebaudioside D, which has a less bitter flavor profile for beverages, is made into a powder form and added to boiling water. To make the powder, the rebaudioside is mixed with a solubilizing enhancer such as a water soluble organic acid or salt and a stabilizer. Lastly, the rebaudioside and solubilizing enhancer solution is spray dried into a powder that can be dissolved in beverages more effectively.[66]

Finally, the structure of the product when using stevia as a sweetener can be different when there is less bulk. This can result in different textures, negative changes to the look of the product, and less desirable mouthfeel. To fix these issues, inulin from chicory root fibers can act to provide important texture aspects to the products while also giving an appealing color. It is also gluten free and can be used to provide product bulk for those who normally cannot consume flour.[65]

Flavor

Stevia Flavor Challenges

Along with formulation issues, stevia faces important flavor challenges. Certain glycosides, like Rebaudioside A and stevioside, can have bitter aftertastes that negatively impacts consumer acceptability.[67] Rebaudiosides with more sugar molecules attached to the steviol backbone are sweeter and less bitter. For example, Rebaudioside D has five glucose molecules and Rebaudioside A has two glucose molecules. This makes Rebaudioside D more sweet and less bitter than Rebaudioside A.[68] Additionally, polar steviol glycosides such as Rebaudioside D, M, and E have a more sweet and clean taste while non-polar steviol glycosides such as Rebaudiosides C, F, and D have a more metallic and bitter taste.[69] Also, certain molecules have different "sweetness peaks" where it can take different amounts of time for the sweetness to hit the taste receptors. It takes more time for rebaudiosides than sucrose for the flavor to reach the taste buds that perceive sweet which drastically modifies the flavor profile.[70] Finally, replacing sugar with stevia does not result in a linear relationship of sweetness replacement. When you add more sucrose, there is more detectable sweetness. When you add more stevia, it does not become more sweet past a certain threshold.[69]

With each formulation issue comes a potential solution. The main solution is combining different rebaudiosides to achieve desired flavor profiles. For example, one formulation of blended rebaudiosides can be used in a sweet and savory food, such as using stevia to counteract the acidity of tomato in a sauce.[70] Sensory analysis is also commonly done to evaluate flavor and taste of stevia in foods. This is used to make sure consumers are likely to enjoy the flavor and identify any negative flavors before the product goes to market.[71] Finally, sweetness modulators are used to combat bitterness and make stevia taste more similar to sugar. These ingredients are used in combination with High Potency Sweeteners (HPS), like stevia, because HPS usually take more time to reach the sweet receptors since they are hydrophobic and stick to proteins. When using a sweetness modulator along with the HPS, the protein is shocked and shrunk to release the HPS back into the saliva to be tasted faster and linger in the mouth less.[72] This produces a more desirable flavor and makes the sweetening agent taste more similar to sugar. Stevia used in foods can be complicated, but with trial and error, reformulations, and sensory analysis it can be made possible.

Recommendations

After analyzing the food system of stevia, seen in Figure 4, many recommendations emerge for effectively achieving the four pillars. Potential marketing approaches are seen in Table 2, where different audiences, approaches, and challenges are noted in order to achieve a desired outcome.

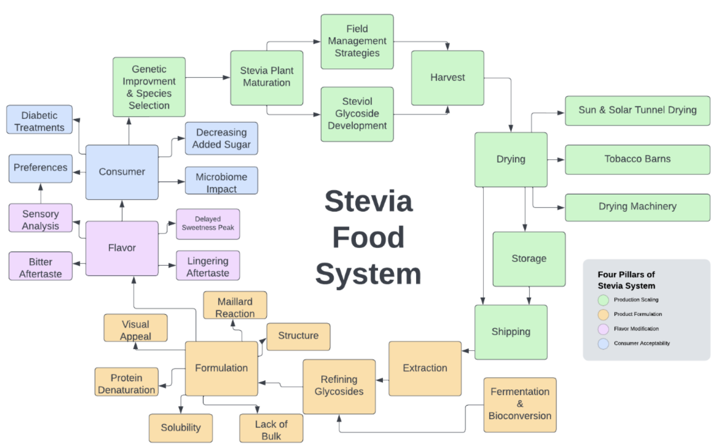

Figure 4: Stevia's Food System and Pillars for System Change

Additionally, Table 3 addresses challenges, solutions, and opportunities for growth in many aspects of the food system from farm to formulation. Altogether, these tables provide areas for improvement and advancement of the stevia food system.

Table 2: Stevia Marketing Approaches

	Target Audience	Approach	Desired Effect	Challenges
Social Media	Younger Generations (10-30 year olds)	Using platforms such as TikTok, Twitter, Instagram, etc., influencers will “set trends” of eating less sugar and more stevia containing products.	People seeing other people consume products peaks their curiosity and urges them to purchase one for themselves. Younger people also tend to follow trends more and buy what is popular. Making stevia “cool” is one way to insert lower sugar consumption into the younger generation’s food system.	Not all of the younger generation is on social media or takes to trends on the internet.
Clean Eating	Middle Aged Generation (40-60 year olds)	Advertising stevia as a healthier choice when choosing what foods to eat. Consumers can still satisfy their sweet tooth while trying to eat healthier and make better food choices.	By advertising stevia as a better way to consume something sweet, consumers may see it as a “clean” approach to changing their diets while still eating things that are desirable.	Products may not taste exactly the same to some. The flavor might not be desirable enough for consumers to make the switch. Also, consumers may not want to switch to stevia-based products all together and choose other alternative sweeteners.
Sustainability	Younger Generations	Advertising the more sustainable	Showing consumers that	Consumers may not see their

	(20-40 year olds) & possibly vegans, vegetarians, etc.	nature of growing stevia compared to other crops like sugar. Showing the use of old tobacco farms converted to stevia farms.	purchasing stevia-containin g products is a way to contribute to "saving the planet". Eating cleaner is one way to benefit yourself and the planet.	direct impact since it is not something that is an instantaneous change.

Table 3: Field to Formulation

Issue	**Challenges**	**Solutions**	**Recommendati ons**	**Opportunities for Growth**
Seed vs. Propagation (starting the plant)	Growing stevia plants from a seed is more challenging, takes longer, and has less success.	Clonal propagation serves to be a more successful and faster mode of stevia repopulation. Transplanted cuttings with 4-6 nodes are more likely to survive.	Propagation can be somewhat laborious, so planning for the allotted time it will take to propagate and grow new plants is vital to success.	Since propagation takes a little longer to get the plant growing, creating a way where seeds grow quicker and provide a higher yield would advance the field.
Soil Moisture	Proper irrigation and drainage are important to keep soil at an optimal moisture level. If the moisture is too low, the plants could wilt and lose leaves. If the moisture is too high, root rot could occur. Both scenarios	Investment in a drip irrigation system helps to maintain a proper moisture level that will maximize yield, plant health, and ultimately profits. Predetermined drainage routes in the field will help decrease	Maintaining a soil pH of 6-7.5 with slightly sandy soils will help grow the highest quality plant.	

	are substandard and will result in overall yield loss.	flooding and manage water control during floods.		
Plant Problems	Leaf blight and leaf spot are diseases which commonly affect stevia plants. Caterpillars and weeds are also common pests.	Heavily affected leaves should be pruned to rid leaf spots and blight. To prevent in the future, improve drainage and reduce shade and nitrogen fertilization.[73] Caterpillars should be removed and a microbial insecticide should be applied.[74] Weeding should be done by hand to decrease yield loss and mulching should be done to prevent future weeds.	Stevia is prone to weed growth after transplantation due to the initial stagnant growth. Mulching and microbial insecticide sprays immediately after planting will decrease future blight.	Making registered herbicides and pesticides that are proven to work and be certified safe for the environment will decrease trial and error by farmers.
Steviol Glycoside Development	Shorter daylight periods of 11 hours or less results in earlier flowering. Once the plant flowers, steviol glycoside synthesis slows, resulting in less quality leaves.	Growing the plant in climates where there are 16 hours or more of sunlight will result in an increased mass and improved steviol glycoside production. Clipping the flower buds as soon as possible will result in	Increased steviol glycoside production will result in sweeter leaves and a more valuable product.	Testing of commercial stevia growth in greenhouses with grow lights year round.

		more development and sweeter leaves.		
Plant Reproduction	Stevia is self-incompatibl e and needs cross pollination.	Bees or flies are used in commercial settings to pollinate the flowers to produce seeds.	Seeds that are infertile are clear or yellow in color while seeds that are fertile are dark or black.	Research and genetic modification on how to make stevia self-compatible in order to save money on pollinator costs.
Leaf Drying	Sun drying of the leaves in the open can expose the leaves to tropical conditions and extreme solar radiation, damaging the leaves.	Shade nets are placed over the leaves to create shade, but still dry the leaves with exposure to the heat.	To prevent stevia leaves' exposure to outdoor elements, solar tunnels, modified flatbeds, and tobacco drying barns are more modern ways of drying the leaves.	Creating an alternative drying method where a central location for drying exists instead of having equipment on each farm. This will save money and boost sustainability of stevia growth.
Leaf Separation	Stems can leach tannins and waxes into the solution if still present during steviol glycoside extraction.	Separation of leaves and stems can be done using a mini-defoliator, continuous leaf-stem separator, or winnowing separator.	Some of the separation methods do not work on wet leaves, so it is imperative this must be done after drying.	Similarly to leaf drying, creating a central location for leaf separation to save on equipment costs. Leaf separation and drying could potentially be next to each other.
Steviol Glycoside Extraction	Each primary extract of steviol glycosides has	Many rounds of refining the primary extract	Continuous refinement of single	Basic research and knowledge sharing of

	different amounts and types of steviol glycosides due to the amount of sun the plant obtained during growth.	will yield a varying amount of each rebaudioside. Each extracted product can be purified to obtain a high quality single rebaudioside extract.	rebaudioside can be costly.	different extraction techniques is needed between companies. Scaling the small benchtop, experimental methods of extraction to a large industry of extraction can be difficult. However, consistent quality and product must be obtained when scaled.
Steviol Glycoside Quality	Each product needs to have a certain percentage of pure steviol glycosides present to achieve a certain ingredient specification requirement. This percentage is usually 95% pure steviol glycosides.	The blending of extraction products with varying percentages of glycoside purities can make a unique product that meets the 95% pure steviol glycoside requirement.	This requirement is highly regulated by the FDA and glycosides need to be 95% pure to be used in product formulation.	
Costly Nature of Extraction	Rebaudioside M, which is made from one of the most favorable steviol glycosides isolated, can be costly to extract since it takes many rounds of	Using stevia Rebaudioside M enzyme genes planted into yeast and fed glucose syrup, fermentation can make Rebaudioside M outside of the	These methods are less prominent than regular extraction due to the cost of materials and technology. Also, many of these methods	Utilizing all rebaudiosides instead of only Reb M. Extracting all separately and then mixing is costly and inefficient, creating a plant

	purification and isolation. It also can result in a low yield since it is not as present in the stevia leaves as other steviol glycosides.	plant. Bioconversion of yeast to stevia plant enzymes also produce Rebaudioside M. Once the enzymes are fed steviol glycosides, they convert the glycosides to Rebaudioside M.	have patents which may restrict the producer from proceeding.	that is "pre-mixed" with certain sugars to create a stevia that tastes good to begin with.
Lack of Bulk	When substituting sucrose for stevia in formulation, the amount of stevia required is not the same as the original amount of sucrose to make it sweet. This leads to a lack of bulk in the recipe.	Maltodextrin is often used in conjunction with stevia to add bulk. Additionally, dried glucose syrup and erythritol could also be used.	Maltodextrin is less preferred by health-conscious consumers due to the high amount of processing. Instead, glucose syrup and erythritol are more favored by consumers and promote a cleaner label.	A rare sugar, allulose, has been gaining consumer praise as positive responses have potential to create increased demand in the market.[75] Allulose has a great bulking capability and can be used with stevia in products to tackle physical bulk, sweetness, and the Maillard Reaction in one.[76]

Lack of Freezing Point Depression	Sucrose normally depresses the freezing point of frozen dairy products, such as ice cream. Depressing the freezing point makes the product more scoopable and have a more desirable mouthfeel.	To achieve the same mouthfeel and depress the freezing point when using stevia is to add erythritol, which also adds bulk.	Making a product that has similar ice cream qualities without the excess sugars will make consumers more likely to repurchase the product.	Many ingredients have a lot of different functions, so use of erythritol along with stevia will provide a bulking effect in addition to depressing the freezing point and curbing metallic tastes of stevia.
Lack of Browning (Maillard Reaction)	Sucrose is a reducing sugar that browns when exposed to heat. Stevia does not have this same effect which may make the product look less desirable.	Adding allulose to the formulation will cause browning since it participates in the Maillard Reaction, similar to sucrose.	People usually eat with their eyes first, so creating a product with a brown color that looks familiar to consumers will increase their inclination to purchase and consume the food.	
Solubility of Stevia in Beverages	Normally, when adding sugar to a beverage the sugars are dissolved into water to make a syrup. With stevia, the syrup made by this method is not as potent and the sweetness is more diluted.	Instead of adding more stevia syrup to get the same effect as sugar, a more cost effective way is to make a new powder solution. Rebaudioside D is ground into a powder and added to boiling water with a solubilizing	Rebaudioside D is used because it has a less bitter flavor profile for beverages.	New flavor modulators and stevia leaf extracts, such as SweetRight by ADM, offer greater solubility and a better mouthfeel for the consumer when used in combination with sucrose.[77] A 50% sugar reduction may

		enhancer and stabilizer. After spray drying the boiled concoction, the new powder can be added to beverages to provide sweetness.		serve as a temporary solution to flavor issues, solubility, and mouthfeel until better stevia products can be made.
Different Mouthfeel, Texture, and Appearance	Without the bulk of sugar, stevia products lack the familiar texture of sucrose-containing baked goods.	To create a similar mouthfeel, texture, and appearance, inulin from chicory root fibers can be added. This boosts the bulk of the product and creates a more desirable mouthfeel.	Inulin also has an added bonus of being gluten free, making a cleaner label for those who cannot consume flour.	
Delayed and Lingering Sweetness	It often takes more time for stevia rebaudioside sweeteners to reach the taste receptors in the mouth which can cause a delayed sense of sweetness and lingering of sweetness in the mouth. These different “sweetness peaks” can negatively affect the flavor profile of the product.	Adding sweetness modulators makes the stevia molecules less hydrophobic, unsticking them from proteins. This causes the stevia sweetener to travel through the saliva instead where stevia is tasted faster and lingers in the mouth less.	Using sensory analysis panels to evaluate the flavor and formulation of products will help to evaluate consumer enjoyment and identification of negative flavors before a product launch.	

Bitter Aftertaste	Rebaudiosides with less sugar molecules attached to the glycoside backbone will cause a bitter aftertaste. Additionally, Rebaudiosides C, F, and D have a more metallic taste.	Mixing different rebaudioside after the purification process will create a sweetener for each purpose. Using Rebaudiosides D, M, and E have a more sweet taste.	Sweeteners can also be used in savory situations, such as tomato sauce. Mixing a formula of rebaudioside specific to the product will make each one unique.	

Conclusion

Stevia has a long history of use dating back hundreds of years. This paper outlines the journey of stevia from farm to fork, emphasizing considerations for scaled production, product formulation, flavor modification, and consumer health benefits. Table 3 provides an overview and recommendations for scaled production and product development. Stevia has the potential to play a major role in sugar reduction along with other emerging alternative sweeteners.

The gradual incorporation of alternative sweeteners into common foods made with sugar ingredients necessitates a cooperative approach throughout the stevia food system including sectors, disciplines, and cultures to effectively address the barriers, challenges, and opportunities within and among each of the four main pillars: decreasing the cost of scaling production, improving product formulation, addressing flavor modification, and maintaining consumer acceptability. The gradual introduction of alternative sweeteners into the American food system could potentially contribute toward greater availability of foods with less caloric density. Ultimately, this could positively influence overall public health through decreased consumption of calories, with the intention of reduced incidences of obesity, and less money spent on healthcare related to obesity, CVD, and type 2 diabetes.

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