The Human Flavorome Project

Current State of Affairs

The Fourth United States National Climate Assessment (NCA4) conducted a survey of scientific literature regarding climate change and found that the annual global surface temperature has increased by 1.0 degrees Celsius over the last 115 years. Additionally, annual precipitation has increased in the northern and eastern regions of the U.S., while simultaneously decreased in the south and western regions of the country. Parts of the U.S. that experience persistent drought are projected to have declines in food production, exacerbated by the expanding range of crop pests and fungal diseases due to elevated average temperatures. These effects of climate change are expected to greatly impact the prices of food at the national and international level.

Additionally, food production accounts for 26 percent of global greenhouse gas emissions. The U.S. alone produces an equivalent of 671.5 million metric tons of carbon dioxide per year (2021) from the agricultural and food sectors, primarily from nitrous oxide and methane emissions. Animal agriculture especially has an outsized impact on the environment, with 14.5 percent of all greenhouse gas emissions produced by the livestock industry alone according to the Food and Agriculture Organization (FAO). Given the negative externalities associated with conventional meat and dairy production, more attention has been paid to reducing consumption of animal products as an approach to limit the environmental impact of human activities.

During COP28, the United Nations Environmental Programme (UNEP) openly endorsed alternative proteins as a means to curb the production of greenhouse gas emissions and reduce water and land usage from global food systems. The production of alternative proteins, which include plant-based meat and dairy analogues, fermentation products, and cellular agriculture products, has been shown to exhibit lower carbon footprints, land usage, water usage, and fertilizer run-off compared to the production of conventional animal products.

Despite the $14.2 billion global investments into alternative proteins in the last decade, poor consumer adoption has limited market penetration of these food products. The most cited factor for consumer rejection of alternative proteins is taste, which remains the top factor that consumers consider when purchasing food products, according to the annual Food and Health Survey conducted by the International Food Information Council (IFIC).

Significant research by commercial enterprises and academic groups has been conducted to achieve higher palatability in alternative proteins. However, these innovations have yet to bring novel food products to market, especially plant-based analogues, that can compete sensorially with conventional and dairy products. Most consumers remain recalcitrant to modifying their dietary habits to accommodate sustainable options, focusing primarily on other factors such as taste, texture, price, and nutrition.

Some of the barriers to innovations linked to the taste improvement of alternative proteins are the highly competitive nature and low profit margins of the food industry. Much of the intellectual property of food formulations and processes is kept hidden through trade secrets and patents so that firms can remain competitive. For example, a high-profile legal dispute occurred between Impossible Foods and Motif FoodWorks regarding patents involving plant-based meat flavors and colors. While alternative protein consortia have been formed between food companies, nonprofit institutions, academic centers, and government entities, these are largely voluntary associations which remain limited in their ability to share technical, formulation, and sensory data. As a result, many food companies in the alternative protein space are largely siloed and must develop their products using internal knowledge to remain competitive in the market. This is especially true of small and medium-sized enterprises (SMEs) without the visibility and financial backing of venture capital to forge useful relationships with these consortia.

Improved Future

Online communities and social networks contain a massive digital footprint regarding the collective human preference for combinations of food ingredients in the form of online recipes. The Human Flavorome Project aims to map this digital culinary landscape by first compiling the concentration of major taste-active compounds in food ingredients. This preliminary compositional data will then be used to explore the relationship between the chemical concentration of these taste components in online recipes and the popularity of those recipes, captured through digital metrics such as views, likes, and engagements on digital platforms.

These data sets will be analyzed for patterns that potentially link human preference for certain foods by evaluating palatability synergies of taste-actives in these culinary combinations. Unlike sensory evaluation panels used by the food industry, where a small number of trained panelists consume a food product and provide numerical outputs based on their subjective perception of specific taste properties, the Human Flavorome Project can take advantage of a much larger pool of digital data, a larger number of food combinations, and potentially examine taste patterns with greater statistical significance. Ultimately, the goal of the project will be to construct a topographic map of human taste preference to certain food combinations.

Libraries of culinary categories will be analyzed and generated to provide roadmaps in achieving optimal taste desired by consumers, based on the chemical profiles of the ingredients themselves. The initial focus of the project will be on savory cuisine, as these insights could have a direct impact on our understanding of the palatability of alternative proteins and other future novel foods. These maps will be designed to guide food entrepreneurs, business owners, startups, and companies in new product design. The hope will be that these knowledge resources will reduce time to market for these commercial ventures during the product development cycle.

Approach

Human taste consists of six basic tastes – sweetness, saltiness, sourness, bitterness, umami, and kokumi. The first three tastes are associated with the presence of sugars, salt, and organic acids, respectively, in foods. These three tastes follow a straightforward quantitative relationship, in which higher concentrations of the taste-active solutes increase the intensity of the taste perception in a relatively linear fashion. Bitterness is much more complex as the 25 known human bitter receptors interact with thousands of molecules that can elicit bitter perception. Despite the importance of bitterness to palatability, due to the difficulties associated with the modeling of bitterness, the effect of bitter compounds will be simplified in this project.

The last two tastes, umami and kokumi, are intrinsically linked to the savory palatability of foods and governed by the presence of specific amino acids, peptides, and ribonucleotides found in food ingredients. The main focus of the Human Flavorome Project will be on these two savory tastes, which have a high impact on the consumer acceptance and enjoyment of savory foods. These two tastes have a unique behavior compared to the other basic tastes. For example, umami is primarily activated by the presence of the amino acid, glutamic acid, and two ribonucleotides, inosinic acid and guanylic acid. Like sugar and salt, glutamic acid increases umami linearly as its concentration increases. However, if inosinic acid or guanylic acid are combined with glutamic acid, the perception of umami is multiplied significantly. As both the concentration of glutamic acid and the ribonucleotides approach a 1:1 ratio, the umami perception can be as great as 7 to 15 times greater than the equivalent concentration of glutamic acid alone.

Kokumi activating compounds, which are principally the antioxidant peptide, glutathione (found in meat, seafood, and mushroom ingredients), and amino acid derivatives known as cysteine sulfoxides (found in Allium vegetables such as garlic and onion), can further amplify savory intensity by as much as 72 percent when they are present at or above the threshold concentration for perception.

Other taste-active categories also play a role on the two savory tastes. For example, a specific concentration of sodium from salt is needed to activate umami compounds, while the taste of sourness from organic acids inhibits the perception of umami. As such, the correct combination of ingredients that contain the appropriate levels of these compounds can have a much greater effect on palatability than each ingredient alone or in other combinations with other taste-active compounds.

Over 350 food ingredients commonly used in cooking have already been compiled from the research literature by the author for their native concentration of taste-actives. Quantitative models have also been constructed based on the human physiology of taste. The models contain much of what is currently known by the author regarding the mathematical relationships between three of the six basic tastes, their taste potentiators, and their effects on palatability. Users can presently input the quantity of different ingredients in a recipe and receive the estimated taste intensity of umami, kokumi, and saltiness. The next step during the Sugarman Practitioner-in-Residence period will be to construct models to estimate the sweetness, sourness, and bitterness.

Following the completion of the basic taste models, data on social media metrics and ingredient quantities from online recipe communities will be extracted and fed into the model to give estimates of palatability. A research literature-based model to estimate the popularity of a recipe based on social media metrics across multiple platforms will also be implemented. The initial runs on small-scale data will be used to validate the models and discover preliminary insights.

Together, relationships between taste palatability and digital popularity can then be explored, quantified, and visualized. These early topographic visualizations and insights will then be packaged into appropriate content pieces, whether as white papers, webinars, infographics, case studies, or a book, that will be openly shared with the greater food industry. The models will also be converted into a web application for easy access by users and expand the potential sources of data inputs.

Following the Sugarman Practitioner-in-Residence Program, more advanced modeling will be developed to determine the effect of cooking and heat processing on the taste-active concentration from moisture loss. Additionally, the chemical kinetics of the taste-actives and how these compounds react or degrade in the presence of other food components will be modeled to further increase the accuracy of the palatability estimations. Pending a sustainable strategy to obtain financial resources through commercial revenue from consulting, custom analyses, subscription services, and other possible services for the food industry, the concentration of taste-actives in food ingredients not yet explored in the research literature will be determined. Finally, machine learning will be applied to the project to analyze larger datasets to identify possible culinary patterns and further refine the mathematical taste and social media metric models.

Anticipated Outcomes

i.) Rational Food Product Design

The vast majority of what we have come to perceive as edible, and even more so, pleasurable to consume, has been largely passed down to us over generations through the form of recipes. Only in the last century has there been more attention paid to deliberate approaches to engineer food formulations based on scientific principles rather than mimicking tradition, custom, or historical pattern. With the growth of alternative protein technologies, the formal design rules are still being written as far as how food ingredients can be formulated to be best suitable for human desires and consumption. One hopeful outcome from the project is that the system will provide a more rational, systematic approach to food design, accelerating the development of more consumer-attractive alternative proteins and other novel foods.

ii.) Novel Taste Combination Units

Through human history, basic combinations of food ingredients were discovered by accident as human experimented with wild food ingredients cooked under imprecise conditions. Over millennia of domestication, experimentation, tradition, and innovation, humans have developed more discrete combinations used for recipes. For example, mirepoix is a well-known combination of vegetables often used as a base for soups or stews in French cuisine. An additional outcome of the project may be the discovery of new novel combinations of food ingredients not yet known in culinary history. These would provide new creative palettes from which chefs, restaurants, and food businesses could draw inspiration to design new cuisines.

iii.) Food Formulation Strategy Shift

Current food formulation is conducted through three main pathways: highly analytically with the assistance of trained sensory panelists to provide quantitative data and then reiterated to improve specific sensory outcomes; directly replicated from known recipes with the addition of additives to improve shelf-life, color, and taste; or semi-empirically through methodical variations of ingredients to achieve a specific sensory outcome. The first approach is expensive and requires significant resources, time, and scientific labor to achieve, normally only available to large food corporations. The second approach limits the food formulator to what is already known from culinary history. And the third approach also requires a tremendous amount of time and resources that are lost through undisciplined experimentation. The hope is that a central repository of sensory insights from all human cuisine could serve as an advanced resource to guide these formulation strategies and reduce loss along the way. These science-driven resources are not normally available to small and medium-sized enterprises (SME), restaurants, and individual entrepreneurs in the food industry. Such a repository may allow these smaller commercial players to be much more competitive in the alternative protein landscape.

iv.) Precursor to Large Taste Models (LTMs)

Much like how large digital databases on human social media interactions and written language have served as the raw data to train large language models (LLMs) to produce language-based outputs, the author hypothesizes that a similar process can be designed to translate human taste perception into data for machine learning. The quantification models designed in this project for evaluating digital recipes could potentially be used as the precursor to larger fine-tuned models that could construct food formulations based on desired sensory parameters or consumer preferences. While artificial intelligence has already been implemented to design flavorings and sensory formulations, most notably by the top flavor houses', Givaudan, Firmenich, and International Flavors and Fragrances (IFF), for food product development, these make use of internal company data to drive their models and remain proprietary. The Human Flavorome Project would provide this data through an appropriate open-source license.

Local Experts

The author hopes to connect with Prof. Matthew J. Salganik and members of his research group to better understand the current state of the art in computational social science. The aim will be to gain insights into the potential opportunities and limitations of using these methods to compute large databases drawn from food digital spaces. In addition, the author aims to discuss with Prof. Elke U. Weber and her research group on the topic of economic decision-making in the context of sustainable choices, which may support a broader understanding of how consumers decide between conventional and alternative protein food products. Conversations with Prof. Peter Singer regarding his work on practical ethics in animal welfare as well as Prof. Michael Oppenheimer's work on climate change and policy may provide valuable intellectual insights for the current project.

The author also plans to have conversations with researchers in the Departments of Computer Science regarding the project. A few potential experts to consult regarding machine learning and computational statistics could include Profs. Ryan P. Adams, Karthik Narasimhan, and Mandy Wang and their respective research groups. Additionally, discussions with research members of the Departments of Chemistry and Chemical Engineering may prove fruitful in evaluating analytical methods for quantifying key taste-actives in food matrices. Example faculty members from these departments could include Profs. Ralph Kleiner and Tom Muir and their lab groups, who research chemical tools to investigate RNA and protein in living systems.

Other groups on the Princeton campus to connect with relevant entrepreneurial experts could include the Princeton Entrepreneurship Council and the Princeton Innovation Center BioLabs.