Informatics for your Gut: at the Interface of Nutrition, the Microbiome, and Technology

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Summary

Background: A significant portion of individuals in the United States and worldwide experience diseases related to or driven by diet. As research surrounding user-centered design and the microbiome grows, movement of the spectrum of translational science from bench to bedside for improvement of human health through nutrition becomes more accessible. In this literature survey, we examined recent literature examining informatics research at the interface of nutrition and the microbiome.

Objectives: The objective of this survey was to synthesize recent literature describing how technology is being applied to understand health at the interface of nutrition and the microbiome.

Methods: A survey of the literature published between January 1, 2021 and October 10, 2022 was performed using the PubMed database and resulting literature was evaluated against inclusion and exclusion criteria.

Results: A total of 139 papers were retrieved and evaluated against inclusion and exclusion criteria. After evaluation, 45 papers were reviewed in depth revealing four major themes: (1) microbiome and diet, (2) usability, (3) reproducibility and rigor, and (4) precision medicine and precision nutrition.

Conclusions: A review of the relationships between current literature on technology, nutrition and the microbiome, and self-management of dietary patterns was performed. Major themes that emerged from this survey revealed exciting new horizons for consumer management of diet and disease, as well as progress towards elucidating the relationships between diet, the microbiome, and health outcomes. The survey revealed continuing interest in the study of diet-related disease and the microbiome and acknowledgement of needs for data re-use, sharing, and unbiased and rigorous measurement of the microbiome. The literature also showed trends toward enhancing the usability of digital interventions to support consumer health and home management, and consensus building around how precision medicine and precision nutrition may be applied in the future to improve human outcomes and prevent diet-related disease.

Keywords
Consumer health informatics, microbiota, user-centered design, telemedicine, information systems

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1 Introduction

The relationship between dietary patterns and the microbiome has surfaced as a critical factor in management of human health, including prevention and treatment of diseases including obesity [1-3], type 2 diabetes (T2D) [2, 4], Inflammatory Bowel Disease (IBD) [5, 6], and more. As research moves towards precision nutrition as a means to mitigate increasing rates of diet-driven disease, many challenges have come into view. Diet is not the only factor influencing rising rates of obesity and T2D. Recent literature suggests that factors such as sleep patterns [7], access to food [8], and time available for food preparation in the home [9] also play a role, for example.

Consumers in the United States face challenges when providing a nutritious diet for themselves and their households, including, but not limited to, low nutrition literacy, food costs, food waste, supply chain shortages, lack of time to prepare meals, and food access. These challenges translate to increased risk for personal health problems as well as increased burden on the healthcare system over time, with diet-driven disease accounting for an estimated 20% of healthcare costs in the United States [10].

Consumers are largely responsible for the management of nutrition and dietary choices in their own lives and households. Even when access to health care providers is available, most primary care physicians have limited time to discuss nutrition with their patients in depth [11]. Existing nutrition research has reinforced the importance of consumer understanding of food composition, preparation, access, and dietary behaviors for prevention, management, and treatment of diet-driven diseases [12-20]. To this end, there are several digital health applications designed to support the consumer in making nutritious food choices and preparing nutritious meals for themselves and their households. The effectiveness of a digital application is tied not only to its accuracy and quality, but also the application’s ability to engage a consumer in a consistent manner [21, 22]. Therefore, the impacts of digital health interventions aimed at behavioral modifications in diet, physical activity, sleep, or wellness are directly tied to consumer adoption and consistent use [23, 24]. The research described in this brief year-in-review survey focuses on the design and development of tools for self-management in an outpatient or community setting. The research highlighted recognizes both the challenges of and needs for self-management tools that support consumer use and engagement, as
well as enhanced rigor when understanding mechanisms that influence our diet, such as the microbiome. This survey aims to provide a means for acknowledgement and understanding of the breadth of relationships and knowledge needed to address diet-related disease from an interdisciplinary informatics perspective.

The diet, the microbiome, and consumer behavior are intrinsically linked. The aim of this survey was to synthesize recent literature describing how technology is being applied to understand health at the interface of nutrition and the microbiome, with a special focus on the perspective of the consumer, as shown in Figure 1.

2 Methods

A survey of the literature published between January 1, 2021, and October 10, 2022 was performed using the PubMed database. The search was performed exactly as written below using the exact query provided:


All results from the search above were downloaded as a comma-separated values (csv) file; after checking for duplicate articles, a total of 139 total papers were found. Inclusion and exclusion criteria (Table 1) were formed around identifying recent literature that focused on the intersection of diet and the microbiome from the perspective of a consumer or a patient managing diet-driven disease at home. For example, diet-driven interventions that were self-managed applied in a patient population would be included, but diet-driven interventions applied to a patient population requiring majority clinical involvement or surgical interventions were excluded. Only studies describing human data in whole or in part (i.e., studies including data from mouse and human) were included.

Articles were screened against these inclusion and exclusion criteria. A total of 45 papers were included in the final survey. A total of 39 of the 45 papers (86.7%) included in the final survey were available freely on PubMed Central and the remaining papers were access through institutional access or interlibrary loan. This survey does not reflect a comprehensive review of the literature but aims to identify emerging themes and trends published in PubMed over the past year on this topic. The citations for the 45 papers and their major theme classifications are listed in Table 2, below. Table 2 reports major themes found in the survey, composition, and references for papers examined for each theme.

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**Fig. 1** A high-level overview of themes and topics covered in this survey. The concept of dietary patterns, impact on the gut microbiome, and impact of literature reviewed on precision medicine and nutrition is inclusive of multiple disciplines, including health informatics and bioinformatics.
Table 1: Inclusion and exclusion criteria used. A table describing the inclusion (top) and exclusion (bottom) criteria used when examining the literature included in this manuscript. Table 1. Inclusion and exclusion criteria used. A table describing the inclusion (top) and exclusion (bottom) criteria used when examining the literature included in this manuscript.

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Published between January 1, 2021, and October 10, 2022</th>
</tr>
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<tbody>
<tr>
<td>Database</td>
<td>PubMed database searched</td>
</tr>
<tr>
<td>Organism</td>
<td>Only include articles focusing on or including human studies/data</td>
</tr>
<tr>
<td>Article Type</td>
<td>Peer Reviewed Original Research, Review Articles only included</td>
</tr>
<tr>
<td>Focus</td>
<td>Microbiome, disease, diet OR</td>
</tr>
<tr>
<td>OR</td>
<td>Usability and feasibility of digital diet self-management OR</td>
</tr>
<tr>
<td>OR</td>
<td>Computational rigor of microbiome analyses OR</td>
</tr>
<tr>
<td>OR</td>
<td>Consumer-based digital health/diet interventions</td>
</tr>
<tr>
<td>Location</td>
<td>Studies from any location were included</td>
</tr>
<tr>
<td>Date Type</td>
<td>Studies using 16s rRNA or metagenomic shotgun sequencing of fecal microbiome data included</td>
</tr>
</tbody>
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<tr>
<th>Exclusion Criteria</th>
<th>Excluded research with a majority focus on singular dietary intervention of commercial supplements OR focus on non-self-managed interventions (i.e., surgical or clinical interventions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency</td>
<td>Excluded research with unclear conflict of interest statements OR lack of clarity in performance of peer review OR concerns regarding quality of experimental design</td>
</tr>
</tbody>
</table>

Table 2: Survey Themes.

<table>
<thead>
<tr>
<th>Major Theme</th>
<th>Papers (#)</th>
<th>Papers (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microbiome and Diet</td>
<td>21</td>
<td>46.67%</td>
<td>[25-45]</td>
</tr>
<tr>
<td>Usability</td>
<td>14</td>
<td>31.11%</td>
<td>[23,24,46-57]</td>
</tr>
<tr>
<td>Reproducibility and Rigor</td>
<td>6</td>
<td>13.33%</td>
<td>[58-63]</td>
</tr>
<tr>
<td>Precision Medicine and Precision Nutrition</td>
<td>4</td>
<td>8.89%</td>
<td>[64-67]</td>
</tr>
<tr>
<td>TOTAL</td>
<td>45</td>
<td>100%</td>
<td></td>
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In this context, “usability” refers to the ability of a product to be used by a consumer. A more thorough explanation on usability is well defined by the International Organization for Standardization (ISO) [68].

3 Results

A total of four major themes were identified in the literature and synthesized by KC, each with its own emerging subthemes: (1) Microbiome and Diet-driven Disease, (2) Usability and Accessibility of Consumer Health Tools, (3) Reproducibility and Rigor of Computational Analysis in the Microbiome, and (4) Precision Medicine and Precision Nutrition.

3.1 Microbiome and Diet-driven Disease

Microbiome. With decreasing costs of microbiome sequencing as well as increased interest in the impact of the microbiome on health, the literature and data availability on this topic is expected to grow. The literature in this review circled around diet-driven disease with major public health implications: obesity/overweight, T2D, COVID-19, Irritable Bowel Syndrome (IBS), Irritable Bowel Disease (IBD), and food allergies/intolerance, among others. The literature on the microbiome and diet also focused on prenatal health (gestational diabetes) and infant health. Notable subthemes observed in this research include (1) continued interest in the impact of singular, short-term interventions on microbiome composition, (2) proliferation of smaller studies on the microbiome in diet-related disease, and (3) implicit need for reliable aggregation and analysis of microbiome data to ensure replicability and rigor when applied in a larger human population.

Diet-driven Disease. Most studies described in this survey capture data in a post-COVID world. It is expected that the COVID-19 pandemic has influenced the gut microbiome due to rapid changes in physical activity, diet, access to food, and exposure to one’s community [39] via mechanisms such as lockdowns, social distancing, isolation protocols, and quarantines. One retrospective study of 3,055 16s rRNA microbiome datasets across 12 countries aimed to find any population level changes associated with the COVID-19 pandemic [27]. Authors separated microbiome data into two groups: countries with higher COVID-19 hospitalization rates and countries with lower COVID-19 hospitalization rates [27]. Diversity in bacterial abundance (measured by Shannon’s alpha) was higher in countries with “high” COVID-19 hospitalizations; this difference was statistically significant [27]. It is possible to speculate on reasons why a relationship between microbiome diversity and COVID-19 hospitalization might be found. Research outside this survey found evidence that hospitalization rates vary due to differences in diet, physical activity, alcohol and tobacco use, and other behaviors [69-71], although this evidence may be conflicting.

Irritable Bowel Syndrome (IBS). The potential impact of supporting patients living with gastrointestinal disease is large – for example, an expected 25-45 million individuals suffer from Irritable Bowel Syndrome (IBS) in the United States [72]. Four studies
examined means to reduce symptoms for individuals living with IBS through dietary management. In one study an oral probiotic was trialed (n=15 adults) with IBS over a period of 4 or 8 weeks [30]. The probiotic, called VSL#3R, contains bacteria from the genus *Lactobacillus*, *Bifidobacterium*, and *Streptococcus* [73]. Microbiome composition studies from before and after the study period detected bacteria from all three genera in the group treated with the probiotic, but found no difference in abundance before and after treatment [30]. Despite this, participants in the probiotic group reported reduction in pain and symptoms [30]. Another study of the gut microbiome collected from n=34 individuals diagnosed with IBS and receiving Cognitive Behavioral Therapy (CBT) as treatment was performed [32]. Interestingly, significant differences in microbiome composition were found between individuals who responded to CBT treatment versus treatment non-responders [32]. This apparent conflict in early results, along with relatively small cohort size, suggest that this is an area that will benefit from efforts to store, share, and re-use microbiome data, as well as efforts to aggregate data for comparison in an unbiased and rigorous way. This concept is supported by a fourth study reviewed in the survey: one study reviewed of women with IBS concluded that there was evidence for further investigation of the relationship between bile acid levels, the microbiome, and its mechanism or role in IBS [45]. These studies demonstrate a changing microbiome in individuals with IBS, but highlight the need for evidence to understand the role of the microbiome in IBS and potential means for treatment.

**Type 2 Diabetes.** Type 2 diabetes (T2D) in the United States has a similarly sized impact on public health: according to the CDC, 33-35 million Americans are estimated to have T2D as of December 2021 [74]. The gut microbiome has also emerged as a focus within the research community to understand T2D and identify treatments and prevention methods [4, 75-77]. Although T2D is a highly researched disease, only one study found passed the inclusion and exclusion criteria. In this study, 405 individuals with T2D found significant differences in taxa present in the fecal microbiome at the genus level according to disease severity [42]. A cursory search of the query “T2D AND microbiome” alone on PubMed for 2021-2023 revealed 1,051 resulting papers, although inclusion of the terms “diet” or “nutrition” on the query vastly reduced the search results. One study from management of lifestyle factors for T2D using digital health applications or mHealth [55] indicates that our search terms used may have excluded some relevant papers in this area.

**Amyotrophic Lateral Sclerosis (ALS).** The microbiome is also being investigated in diseases not traditionally thought to be “diet-driven”. For examples, a study of 66 individuals with Amyotrophic Lateral Sclerosis (ALS) and 73 controls found a significant difference in abundance of certain taxa in the fecal microbiota of individuals with ALS [44]. Outside of this survey, there is some research on diet and development of ALS, but diet is not currently considered a causal factor [78, 79]. It is important then to recognize that although there is evidence of the impact of diet on the microbiome, that the microbiome may also be a potential tool for prevention, diagnosis, and treatment of diseases not traditionally considered “diet-driven”. Rather, the microbiome should be considered an important factor in human health that can be modified by dietary behaviors.

**Pregnancy.** Three studies focused on microbiome during pregnancy and during the postpartum period. A study of n=115 pregnant individuals with and without gestational diabetes found no significant difference in microbiome composition or alpha diversity, although some significant changes in bacteria at the genus level were found in the third trimester [26]. The authors of this study state that their work adds to existing studies [76, 80-83] on microbiome changes in pregnancy, noting a knowledge gap and need for further studies of the microbiome during gestation [26]. A 2022 study of 90 infant-mother pairs examined the relationship between maternal weight (overweight or obese) on infant microbiome, also finding no significant associations between the microbiomes of infants born to individuals who had developed gestational diabetes versus not [31]. Outside of gestational diabetes, a study of n=48 pregnant individuals found evidence for an association between diet and decreased alpha diversity in the fecal microbiome, speculating that pre-term birth may have links to the microbiome [41]. This implicates diet as a modifiable factor through which maternal and infant health can potentially be addressed [41]. These studies again demonstrate a changing microbiome in pregnant individuals but highlight the need for evidence to understand the role of the microbiome before, during, and after pregnancy. The literature reviewed also suggests the importance of postnatal support for caregivers of infants and children in managing household tasks. This trend is continued in the *Infant Diet* themed literature, below.

**Infant Diet.** Food allergies and intolerance in infancy emerged as a trend in microbiome studies examined. One study on 30 infants examined microbiome composition between infants fed a typical cow’s milk-based formula versus a hydrolyzed formula (often used for infants with dairy intolerances), observing significant differences in microbial composition after 4 months, as well as observing *Ruminococcus gnavus* as a taxa on that significantly differentiates between the two groups [29]. Another study of 148 infants with a cow’s milk protein allergy found a significant decrease in symptoms, caregiver burden and healthcare resources when a symbiotic was prescribed alongside specialized formulas versus no symbiotic [38]. Considering the rapid growth and establishment of the infant gut microbiome as well as its impact on health, it is unsurprising that these studies on infant diet and microbiome have begun to emerge. A study of 28 preterm infants found a significant difference between microbiome composition and growth in head circumference, especially in the phyla *Bacteroidota* and family *Lachnospiraceae* [33]. This literature also implicitly suggests the importance of postnatal support for caregivers of infants and children in managing household tasks such as feeding, grocery purchasing, and food preparation especially in infants with specialized feeding needs. These needs may be addressed using digital health interventions or informatics approaches.
Microbiome and Diet. Five studies focused on understanding diet and the microbiome, continuing an existing trend in the literature. A 2022 review described the current knowledge on the role of the gut microbiome in lipid metabolism and short chain fatty acid modulation [28]. The authors acknowledge the impact of diet on the microbiome, including how quickly the microbiome reacts to changes in dietary composition, timing of meals, fiber intake, and impact of micronutrients [28]). One study performed a week-long at-home immersion experience for 74 participants focusing on improving behaviors in physical activity and diet [35]. The authors report that anti-inflammatory taxa increased in the microbiome of participants after the intervention [35]. Another study examining long term dietary intake effects on the microbiome (n=128 adults) found an association between self-reported carbohydrate intake and gut microbiome composition [44]. A study of 59 individuals aged 40-85 found no significant changes in fecal microbiome composition’s alpha diversity by age. However, authors did report age-related differences in microbiome composition from samples taken from salivary and gastrointestinal sites [37]. The results of these four studies highlight a need for larger microbiome studies, how the microbiome is captured, and the diversity of evidence that is building our understanding of the gut microbiome. Lastly, a larger cohort study of diet and microbiome in n=3,308 participants reported taxa that was able to differentiate between individuals consuming high levels of animal protein versus low levels of animal protein [34].

3.2 Usability and Accessibility of Digital Health Applications

This literature survey focused on digital interventions that could be self-managed: this includes improving, tracking, or monitoring modifiable behaviors for patients or consumers who are managing their health at home. The subthemes that emerged from this literature were consistent despite a broad array of research topics and foci: Applications intended to support or enhance lifestyle factors impacting health need to be easy to use, easy to learn, fast, accessible, and perceived as useful. Noncompliance was when users experienced technical issues, or when an application or intervention was not convenient to use.

There is a wealth of diet-driven applications already online: food trackers, meal planners, label scanning applications, weight loss programs, and fasting trackers are all examples. Demand for consumer support in pursuit of health and wellness is high. Similarly, a focus on usability and feasibility of prototype applications and interventions emerged in the literature.

Applications Examining Diet or Physical Activity Exclusively. Four studies focusing on exclusively diet or physical activity applications were reviewed. A web-based application for management of dietary patterns, eNutri, was evaluated for usability using the System Usability Scale using n=106 participants in Germany [24]. Participant feedback demonstrated above average usability but stated concerns about the amount of time required by the application to complete its purpose (26.7 minutes, mean) [24]. Another approach aimed to design a “user-centered” dietary management tool for type 2 diabetics, surveying 21 individuals over 4 project phases to understand user needs [50]. The study revealed participant’s desire for ease of access to information, ease of communication, provision of information/content that is easy to understand to accommodate a busy lifestyle [50]. Physical activity-only interventions were also reviewed. A 2022 mHealth study of a smartphone application designed to encourage physical activity was performed to compare usability and enjoyment [46]. A total of 20 participants gave feedback on the system, and results indicated that technical issues when using the application negatively affect use [46]. A separate study of a Bluetooth-enabled resistance band for enhancing strength reported positive feedback on usability in terms of ease of use, ease of learning, and user satisfaction [56]. These studies highlight the importance of user-centered design in lifestyle management applications designed to support behaviors that improve positive health outcomes.

Diet, Sleep, and Physical Activity. Four studies examined applications or interventions designed to support multiple lifestyle factors versus one single factor (i.e., diet, exercise, sleep), especially in vulnerable patient populations. Authors of a 2022 study (n=17) on user experience with a web-based weight management application found important factors to enhance use for self-management of diet and physical activity in kidney transplant recipients [47]. An mHealth application supporting healthy diet, physical activity, and sleep habits for wheelchair users (n=14) also concluded that successful user engagement relied on ease of use, usefulness, and ease of learning [23]. For this study, users also demonstrated interest in personalization of the application, ability to access user history, and access to personalized insights based on their input data and behaviors [23]. A prototype application designed to support improved health behaviors in n=50 prediabetic participants shared results supporting a focus on applications that are easy to use and perceived as useful [55]. A much larger study of over 16,000 users of a phone-based app for self-management of T2D reported that app engagement was associated with improved patient outcomes (as measured by blood A1C) [49].

Applications for Parents and Caregivers. As described previously, food allergies and intolerance in infancy emerged as a trend in microbiome studies examined. Mirroring this trend, four studies were reviewed that reflect the use of technology to support parents and caregivers. A 2022 study of n=126 postpartum individuals evaluated subject use of applications meant to track infant feeding patterns, including feeding times, duration, volume of feed, and more [48]. Most of the subjects (n=72) who used the infant feeding application used it for logging or tracking; factors describing their support for use of a tracking app included ease of use and ability to use with a co-parent or co-caregiver [48]. A 3-phase study to evaluate design needs for a social and emotional well-being application in Aboriginal and Torres Strait Islander women concluded that app design for this approach requires extensive end-user consultation and investment in user-centered design [53]. A study of n=45 parents of newborn infants was performed to discern end-user needs for a
The literature on microbiome sample collection, sample processing, nucleotide extraction, sequencing, and data freely acknowledges concerns around data quality, reproducibility, and the need for quality assessment and control. As microbiome data gathering becomes cheaper and calls for improved biomedical data management standards increase [84], the need for these methods will continue to grow. Tools, methods, or calls for enhanced data management infrastructure, re-use, and code sharing were described.

**Removal of Bias in Microbiome Analysis.** Many microbiome datasets have small sample sizes, and there is interest in means to compare, combine, or otherwise aggregate results to see which findings can be generalized. Methods, applications, and recommendations for this type of broad scale comparison and quality assessment in microbiome data were proposed in the literature to correct for environmental batch effects [58], for population-level data stratification [36], filtering of rare taxa for reproducibility and generalizability [63], among others. Reproducibility continues to be present as a topic of interest, including a method (RESCRIPT) for enhancing reproducibility of reference databases commonly used for taxonomic identification in microbiome analysis [60].

A review performed in response to challenges in defining a microbial association network in an environment that is not biased by experimental or computational artifacts, calling for focus on benchmarking and validation [59]. There is a need and enthusiasm for training materials on microbiome composition analysis as demonstrated by sessions provided for the microbiome analysis software QIIME2, with requests for additional trainings on reproducibility and workflow documentation [61].

**The Future of Artificial Intelligence in Microbiome Research.** A review on machine learning in the microbiome space proposed recommendations for reliable application of artificial intelligence for precision medicine, including creation of standards, increase in quantity and quality of microbiome data, application of appropriate data management solutions such as the Findable, Accessible, Interoperable, and Reusable (FAIR) data principles, and support for interdisciplinary team science [66]. A similar review examining machine learning challenges in human microbiome data echoes a need for larger studies of a certain quality, experimental and computational bias, and need for interpretability of machine learning model outputs [67].

**3.4 Precision Medicine and Precision Nutrition**

Precision medicine and precision nutrition were emerging topics that encompassed multiple disciplines within the computational health and biology space. There is massive interest in the role of the microbiome in precision medicine [85-87], both generally and for specific applications such as the treatment of cancer [88] and to enhance pharmacologic intervention [89]. This interest extends to the relationship between nutrition and the microbiome. In May 2020, the National Institutes of Health described the role of nutrition informatics in its 2020-2030 Strategic Plan for NIH Nutrition Research, which details four questions as a part of its strategic approach: “What do we eat and how does it affect us?”, “What and when should we eat?”, “How does what we eat promote health across our lifespan?”, and “How can we improve the use of food as medicine?” [90]. Answering these high-level questions requires interdisciplinary, team-science based approaches that span the translational science spectrum, from bench to bedside. As methods for capturing dietary behavioral data, food composition, provenance, and preparation data improve, and our understanding of the impact of dietary patterns on the microbiome improves, it is possible to imagine a future where the interface of bioinformatics and health informatics is more clearly realized.

**Future Trends.** Trends discussed through research studies and reviews examined clearly outline diet-driven diseases as a target for precision medicine and nutrition. Obesity is one a high-impact target for the development and application of precision nutrition approaches. A 2021 review predicts that future applications of microbiome research to benefit precision nutrition will include manipulation of the gut microbiome through diet, pre- and probiotic supplementation to alter microbiome composition, as well as fecal microbiota transplantation for treatment of disease [25]. A perspective article in PNAS notes the relationship between the microbiome and health inequities [65]. Therefore, it can be recognized as a tool for researchers to examine as a modifiable factor to improve human health in those populations experiencing health inequity [65]. One study, upon finding differences in fecal microbiome taxa between obese and non-obese African American children (n=30) aged 6–10 years old, speculated on a need for personalized approaches that are inclusive of ethnicity and other factors.
4 Discussion

Technology is allowing for the scientific community to bridge the gap between health informatics and bioinformatics for the understanding of nutrition and the microbiome. This work identified major themes in (1) Microbiome and Diet-driven Disease, (2) Usability and Accessibility of Consumer Health Tools, (3) Reproducibility and Rigor of Computational Analysis in the Microbiome, and (4) Precision Medicine and Precision Nutrition. While each of the individual themes on usability and accessibility, microbiome and diet, and reproducibility has a clearly defined limit to its scope, these limits have potential for overlap through the application of technology and informatics. The possibility of digital dietary applications for supporting modification of the gut microbiome has great potential for improving health outcomes, for example. However, researchers pursuing these pathways must also be aware of the need for user-centered design in their applications, the reality of food access challenges, and the need for rigorous research supporting recommendations based on existing microbiome data.

Approximately 60% of the United States population experiences diet-related chronic disease such as overweight/obesity, heart disease, stroke, or T2D [91, 92]. Approximately 56 million adults aged 65 and older currently live in the United States, and up to 60% of those individuals are estimated to experience malnutrition [93,94]. Another 10% of the United States population experiences physician-diagnosed food allergies and/or intolerances [95, 96]. There is great potential to enhance disease prevention via technology and precision nutrition, but research in this area must address the factors of health equity that play into making dietary choices that fuel positive outcomes. This includes developing technology to support those choices that is easy to use, easy to learn, fast, personalized, and addresses gaps in health literacy found in vulnerable populations [97-99]. This also includes acknowledgement of research demonstrating that purchase and preparation of nutritious food in the home requires time, effort, and support [20, 100, 101].

From a bioinformatics perspective, there is great potential for continued microbiome research and its relationship to dietary patterns to enhance human health. The literature reviewed on microbiome research in this survey demonstrates a need for methods to compare and aggregate data, a need for reporting standards, workforce training, and needs for understanding challenges in both experimental and computational reproducibility and generalizability in microbiome analysis. This requires engagement of the informatics community and resources to build data sharing and re-use infrastructure, as well as communication of biases and challenges in data analysis. This charge is supported by existing work in the literature [102-105].

5 Conclusions

A survey of recent literature exploring the relationships between technology, nutrition, and the microbiome, and self-management of dietary patterns was performed. A total of 45 papers relevant to the inclusion and exclusion criteria were examined for major and minor themes, including:

1. Microbiome and Diet-driven Disease, with subthemes focusing on the impact of diet on the microbiome, diet-driven or related diseases including but not limited to IBS, T2D, overweight/obesity, pregnancy, and infancy;
2. Usability and Accessibility of Consumer Health Tools, with subthemes focusing on digital health applications to support subset populations in diet, physical activity, sleep, or combinations of all three and other lifestyle factors. Subthemes highlighted user needs of caregivers and parents in their caregiving roles;
3. Methods, Reproducibility, and Rigor, with subthemes including removal of bias in microbiome analysis and the potential for artificial intelligence in microbiome research;
4. Precision Medicine and Precision Nutrition, with a focus on how these will be applied in the future to improve human health.

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