NUTRITION AT THE CROSSROADS: FOOD AT THE INTERSECTION OF ENVIRONMENTAL, ECONOMIC, AND SOCIAL SUSTAINABILITY

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NUTRITION AT THE CROSSROADS: FOOD AT THE INTERSECTION OF ENVIRONMENTAL, ECONOMIC, AND SOCIAL SUSTAINABILITY

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EDITORIAL
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Editorial: Nutrition at the Crossroads: Food at the Intersection of Environmental, Economic, and Social Sustainability

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Editorial on the Research Topic

Nutrition at the Crossroads: Food at the Intersection of Environmental, Economic, and Social Sustainability

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Societies around the world are at a critical juncture. As the planetary population grows, there are increasing demands for expanding available food, more nutritious and healthy foods, and contemporaneously the need for greater efficiencies and decreased impacts upon the environment.

The sustainability of food production systems is a complex issue that requires a global and multidisciplinary approach, combining not only agronomy, ecology, nutrition, epidemiology, processing, energy use, but also marketing and sociology. It is within this context that this special issue aims to illustrate, through review articles, case studies, as well as modeling and simulation studies, some means of understanding the integration of food, in a broad sense, within our environment and society.

For example, currently consumption of meat products is being challenged both environmentally and nutritionally, and the transition to alternative protein sources is being encouraged. However, a better understanding of the links between livestock breeding, feeding, environmental impacts, and the nutritional quality of meat and dairy products produced could improve the sustainability of these food choices. On the other hand, consumer demand for a healthier and more sustainable diet, which may lead to the consumption of new products, such as insects, requires the implementation of specific dissemination strategies and government programs, integrating marketing, economic, and psychological aspects. Technological challenges are also addressed in this special issue, with an overview of various strategies adopted by many food companies to reduce energy and water consumption. Among them, the use of new non-thermal technologies is a promising way to improve the sustainability of food processing by reducing environmental impacts. In addition, key issues concerning the development of packaging with reduced ecological footprints are also presented. A focus is also placed on the importance for companies to integrate environmental and social sustainability markers into industrial performance indicators.

Although not exhaustive, we have attempted to cover multiple facets of food systems in this Research Topic. For example, several articles focus on food processing factories and operations; others focus on ingredients and food choices; while others discuss business operations. Some have as a primary focus empirical data, others utilize survey information, while others pursue simulation and modeling. Nikmaram and Rosentrater provide an overview of recent technologies and advances in energy and water efficiencies in food processing factories. Picart-Palmade et al. provide a deep discussion about various non-thermal technologies, and how these are improving the efficiencies of food processing operations. Guillard et al. discuss advances in packaging materials and how these are improving the sustainability of food systems, especially within the context of circular economies. Dohmen and Raman focus on human diets, education, prices, and food choices. Provenza et al. explore which type of beef and dairy production are more sustainable—pasture or feedlot-raised—as method of raising/feeding will impact environmental impacts. Berger et al. investigate insects as a source of proteins, and whether they can live up to their promise as a sustainable food source for humans. Finally, Duman et al. model the integration of environmental and social metrics using a Balanced Scorecard approach for food production business operations.

This issue is especially timely since, in an era of big data and predictive analysis, managerial reliance on modeling and simulation have never been greater. Today, the wide availability of data collection, storage, and dissemination tools have fostered efforts to create more intelligent, better informed, and data-driven decision making platforms. Collectively these can provide a means for internal and external optimization of business operations, and can ultimately improve the environmental and societal impacts of products and processes. Simulation models and analysis tools also allow tracking and recording of real-time data that can be inputted into performance evaluation systems. In integrated systems these types of models and analyses not only provide a better understanding of the issues, but also make it possible for internal and external criteria, and their interrelations, to be assessed in the analysis. Thus, resource utilization, risk identification, forecasting, and performance evaluation can be dynamically quantified.

Indeed, assessing and improving the global food system is highly complex, even when considered from a regional viewpoint or an industry-specific standpoint. This Research Topic covers some facets of the food industry, but not all. For the interested reader, many other references are also available. A few of these include Burlingame and Dernini (1), SUSFANS (2), Tuomisto (3), and Willett et al. (4).

Additional resources can be found in other Research Topics that have been published in Frontiers in Sustainable Food Systems, including livestock nutrition, soil carbon, modeling agro-ecosystems, urban agriculture, food waste, and many more. These can be found at https://www.frontiersin.org/journals/sustainable-food-systems#research-topics.

We would like to thank all of the contributing authors to this Research Topic. It is encouraging to see such innovative work. We hope that you, the reader, also find this Research Topic interesting and useful. And hopefully this helps to spur the conversation about food, systems, and steps that can be taken to improve environmental and social sustainability as the industry tries to achieve the goals of an abundant, nutritious, safe, and environmentally-friendly food supply.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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ORIGINAL RESEARCH
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Integrating Environmental and Social Sustainability Into Performance Evaluation: A Balanced Scorecard-Based Grey-DANP Approach for the Food Industry

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In addition to retaining high levels of customer satisfaction, sustainability of businesses is also heavily reliant on the efficiency of their internal and external processes. Continuous performance evaluations using key performance metrics to leverage operations are essential in maintaining a sustainable business while achieving growth objectives for revenue and profitability. Traditionally, companies have considered various financial criteria, quality characteristics, and targeted levels of service as their primary factors for performance evaluation. However, increasing environmental and social awareness and accompanying governmental legislations are now requiring companies to integrate these two aspects into their performance evaluations. With this motivation, this study proposes a Balanced Scorecard (BSC)-based approach combining Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Analytic Network Process (ANP) methodologies for performance evaluation. The grey system theory has been utilized in order to capture the vagueness and the uncertainty in decision making. To demonstrate the functionality of the approach, a case study is conducted on a U.S.-based food franchise. The results of the algorithm and a discussion elaborating on the findings are provided.

Keywords: sustainability, food industry, performance evaluation, balanced scorecard, grey systems theory, DEMATEL, ANP

INTRODUCTION

The food industry has always been one of the essential contributors to the United States economy. The USDA (U.S. Department of Agriculture) Economic Research Services stated that in 2016, with a 12.6% share, the food and related industries ranked third after housing (33%) and transportation (15.8%) in a typical American household's expenditures (1). According to the U.S. Bureau of Economic Analysis report published in the same year, the contribution of the food services and drinking places contributed to the Gross Domestic Product (GDP) 400.7 billion dollars (2). With a 227.3 billion dollar revenue in 2016, the fast food industry obtained the highest share in this market with an expect annual growth rate of 1.8% in the following 5 years (3).

Although the fast food restaurant sector is expected to grow at a flat rate, the industry has struggled due to the shift in consumer preferences with customers moving away from unhealthy and saturated food products over the last 5 years (3). As forecasts indicate that this healthier food trend will continue in the foreseeable future, major fast food retailers have been expanding their menus to include healthier options to prevent growing numbers of obesity, diabetes and other related health issues. Increasing focus on societal well-being has also shaped the business strategies in other aspects resulting in fast food retailers making community involvement, local supplier support, environmentally benign operations more visible in their business strategies.

For instance, the collaboration between Domino's and St. Jude Children's Research Hospital has raised more than 38 million dollars since 2004 (4). Ben and Jerry's has been using only fair trade ingredients. The company also developed a sustainability program for dairy farms in its home state, Vermont (5). Starbucks, in addition to being one of the top purchasers of renewable energy from the U.S. Environmental Protection Agency, pioneered collaborative farmer programs and activities, including Coffee and Farmer Equity (C.A.F.E.). Practices, farmer support centers, farmer loans and forest carbon projects is another example of such efforts (6).

Business operations has also seen a significant impact as a result of sustainability. The triple bottom line, a.k.a. environment, people, and revenue, are now considered to be integral parts of daily operational decisions since they are vital for business success. Therefore, measuring and evaluating environmental and social sustainability indicators are as crucial as the operational and financial ones in performance assessments.

The locavore strategy aims at encouraging consumers to purchase locally grown and sold food. The green image is an indicator of the overall perception regarding environmental friendly activities. Most performance evaluation methods fall short in addressing several sustainability aspects such as supporting locavore strategies and promoting green image. Furthermore, most studies utilize conventional Analytic Hierarchy Process (AHP) methodologies where only independent and hierarchical criteria are considered and do not include the interdependencies and interactions among the decision criteria. With this motivation, this study presents a Balanced Scorecard-based holistic performance evaluation framework that integrates environmental and social sustainability criteria into performance evaluation. Proposed approach measures the influences of each criterion on others leading to more reliable and accurate assessments. This novel approach extracts the weights of main and sub-criteria without requiring additional pairwise comparisons. Uncertainty and vagueness are also additional factors that are considered in the model.

The paper has the following structure. The literature review, providing information regarding the related work, is provided in section Literature Review. In this section, the focus is on the performance evaluation practices in food industry, the Balanced Score Card (BSC), Decision-Making Trial and Evaluation Laboratory (DEMATEL), and Analytic Network Process (ANP) methodologies, and Grey Systems Theory, respectively. Section Problem Description provides the problem description. A detailed explanation of the proposed methodology is presented in section Materials and Method. The practical application of the methodology is delineated in section A Food Industry Case Study with the help of a food industry case study. Conclusions and the implications of the work for future research are given in section Conclusions and Discussion.

LITERATURE REVIEW

A sustainable business contributes to sustainability by delivering economic, social, and environmental benefits simultaneously (7). To ensure their longevity, these deliverables need to be continuously measured and evaluated through periodical audits (8). Thus, similar to other service industries, integrating environmental, and social sustainability measures into performance evaluation has also become a necessity in the food industry. Motivated by this need, Gerbens-Leenes et al. (9) presented the findings regarding the use of environmental indicators for food production and proposed a method for measuring the environmental sustainability in food production systems. Salvá et al. (10) developed an audit tool for environmental measurement in the UK food sector. Maloni et al. (11) presented a detailed framework of unique Corporate Social Responsibility (CSR) applications in the food supply chain including animal welfare, biotechnology, environment, fair trade, health, and safety, and labor and human rights. Furthermore, in her study, Hartmann et al. (12) connected the rich body of literature on CSR to the food sector.

The balanced scorecard is a widely used strategic planning tool for performance measurement where financial and non-financial measures are integrated with corporate visions. In the literature, a variety of studies apply BSC to various fields including finance, human resources, supply chain management, sales, and marketing, and so on in order to pursue an effective and efficient visionary improvement of an organization. Even though the BSC model is proposed by Kaplan and Norton in 1992 (13) is more applicable for the operations of the profit-oriented organizations, the BSC model is also applicable for the socially and environmentally concerned processes, where particular characteristics of these processes that give emphasis on how well the organization fulfills its mission is considered (14–16).

Several studies on BSC also involve sustainability approach in order to implement the performance evaluation center around multi-criteria decision-making approaches. Kongar (17) proposed a Green BSC approach combining with Linear Physical Programming (LPP) to measure the performance of supply chain management while defining the appropriate measurement criteria. Tsai et al. (18) utilized the sustainability balanced scorecard as a multi-criteria framework for socially responsible investment evaluation. Hsu et al. (19) utilized Fuzzy Delphi Method and ANP to construct a sustainability balanced scorecard framework to measure the sustainable performance for the semiconductor industry in Taiwan. Bhattacharya et al. (20) used a using fuzzy ANP-based balanced scorecard to determine a green supply chain performance measurement framework. Rabbani et al. (21) integrated sustainability balanced scorecard, ANP, and COPRAS (Complex Proportional Assessment) techniques to evaluate the performance of oil producing companies in Iran.

Decision-Making Trial and Evaluation Laboratory (22, 23) and Analytic Network Process (ANP) (24) are two well-studied methodologies in the Multi-Criteria Decision Making (MCDM) field (25). Various combinations of these two approaches have also been developed to determine the influences and interdependence among the evaluation criteria (26). The DEMATEL-based ANP (DANP) is the general form of cluster-weighted ANP. Traditional ANP requires the unweighted super-matrix to be built based on pairwise comparisons. The criteria weights are then obtained by limiting this super-matrix. In order to avoid the need for additional pairwise comparison data, DANP forms a comprehensive unweighted super-matrix by building the direct influence matrix where pairwise comparisons are included within clusters. After the unweighted super-matrix is built, the total relation matrices between clusters are utilized to construct the weighted super-matrix. Details of the approach in addition to its various applications can be found in Chen et al. (27), Chiu et al. (28), Hsu et al. (29), Hung et al. (30), Lee et al. (31), Liou (32), Wu, (33), Wu and Lee (34).

Uncertainty and incomplete information are two issues commonly encountered in multi-criteria decision making environment. Decision makers tend to use linguistic preference relations to express their preferences where there is lack of information (i.e., lack of numerical values for comparison). However, these linguistic preferences usually contain uncertainty and vagueness in the decision making process. Grey system theory (35) can be utilized to address these uncertainty issues. It provides an approach for analysis and modeling of systems with limited and incomplete information, and which may exhibit random uncertainty (36). Grey system theory research areas contain systems analysis, data processing, modeling, prediction, as well as decision making (37, 38). In their literature survey, Tozanli et al. (39) stated that the total number of studies incorporating grey system theory has increased significantly over the past 5 years including the publications in sustainability and MCDM fields. Golmohammadi et al. (40), developed a two-phased grey decision making approach to the supplier selection. Fu et al. (36) applied a grey DEMATEL approach to evaluate the green supplier development programs at a telecommunication systems provider. Furthermore, Dou et al. (37) used a grey-ANP method to identify green supplier development programs. Chithambaranathan et al. (41) applied a grey based hybrid MCDM framework for evaluating the environmental performance of service supply chains. Çelikbilek and Tüysüz (42) proposed an integrated grey MCDM approach for the evaluation of renewable energy sources.

A review of the existing literature reveals that no earlier study combining Grey System Theory, BSC, and DANP methodologies has been proposed to integrate environmental and social sustainability criteria into performance evaluation in the food industry. To the best of our knowledge, this study is the only research determines the weights of influenced criteria in franchised food retail stores via utilizing the methods mentioned above.

PROBLEM DESCRIPTION

Increasing awareness of environmental and social sustainability has resulted in many companies making significant investments to integrate these measures into their performance evaluations. Determining the performance criteria and the criteria weights based on the particular industry in focus have been the subject of several studies in the literature. Compared to conventional manufacturing industries, establishing appropriate measures for service industries is a more challenging task. Particularly, as mentioned in section Introduction, fast food restaurant businesses are striving hard to implement various sustainable practices in that are suitable for the specific operations. Therefore, there is a need for an approach capable of considering the specific needs of businesses when defining the sustainability measures for that particular business.

Traditional AHP is highly capable of obtaining criteria weights via pairwise comparison in a hierarchical structure. However, the contemporary research in multi-criteria decision-making suggests that the evaluation criteria are influenced by one another and hence need to be represented as a network instead of hierarchically. With this motivation, this study propose a Balanced Scorecard-based DANP approach to determine the weights of the criteria. A case study in the food industry is also presented to illustrate the applicability of the proposed model.

MATERIALS AND METHOD

Kaplan and Norton (43) stated that the interrelation between the four perspectives of a typical Balanced Scorecard could be represented by a strategy map. Strategy map is a blueprint any organization can follow to align processes, people, and information technology for higher performance. Therefore, this study utilizes a Balanced Scorecard based Grey-DANP approach to determine the appropriate weights of the evaluation criteria. **Figure 1** provides the steps of the methodology. The details of the methodology are provided in the following.

Grey System Theory

Grey system theory was first introduced by Deng et al. (35) to deal with insufficient and incomplete information. In grey systems theory, a system is called a *white system* if the system information is fully known; and a *black system* if the information is not known at all. A system with partially known information is called a *grey system*. A grey number is a number with uncertain and/or incomplete information and can be mathematically expressed as $\otimes X = \left[\underline{X}, \overline{X}\right] = \{X| \ \underline{X} \leq X \leq \overline{X}, \quad \underline{X} \ and \ \overline{X} \ \epsilon \ R\}$. Thus, $\otimes X$ contains two real numbers $\underline{X}$ (the lower limit of $\otimes X$) and $\overline{X}$ (the upper limit of $\otimes X$) is defined as below:

- If $\underline{X} \to \ -\infty \ and \ \bar{X} \to \ \infty$, then $\otimes X$ is a black number with no meaningful information,

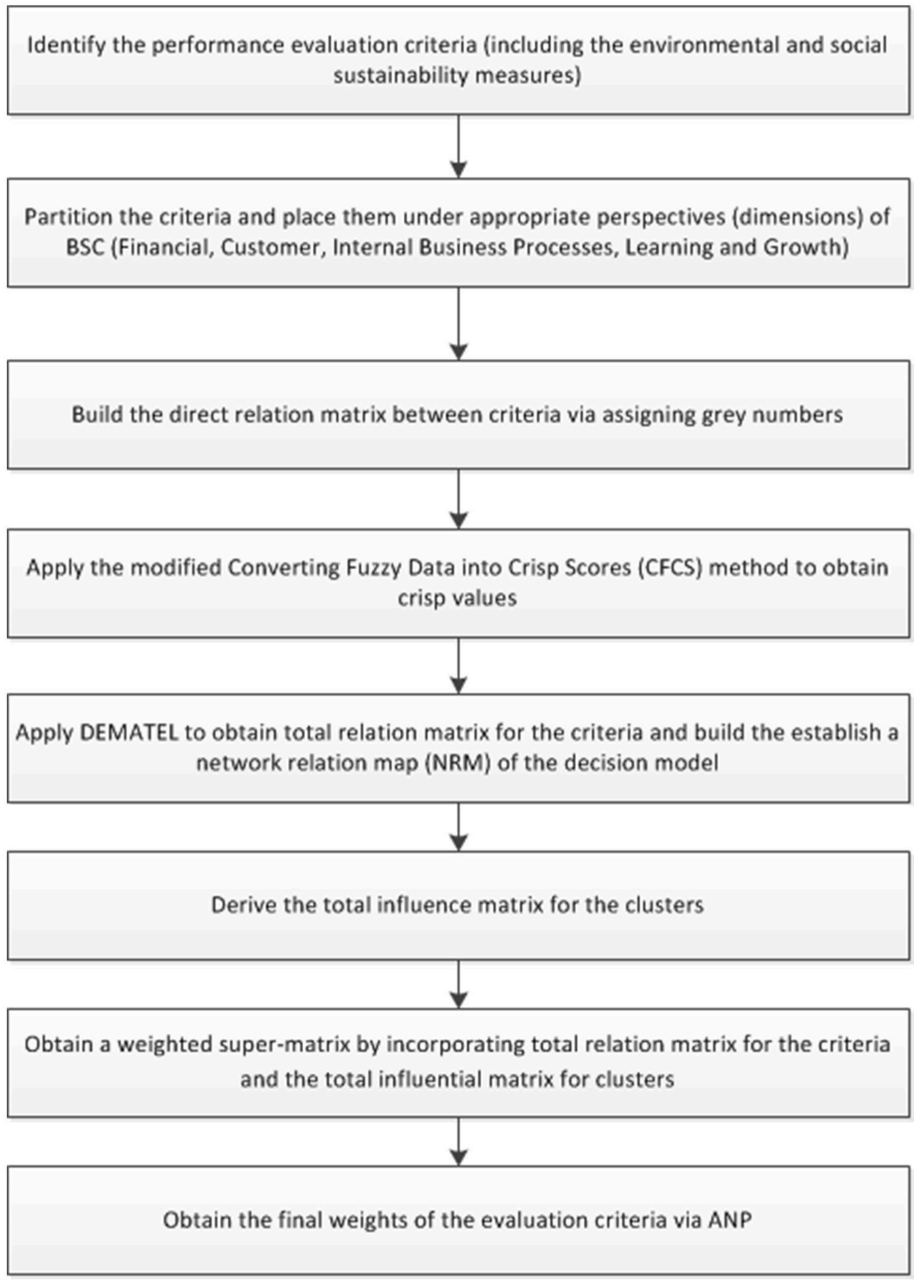

FIGURE 1 | Schematic representation of the proposed methodology.

- Else if $\underline{X} = \bar{X}$, then $\otimes X$ is a white number with complete information,
- Otherwise $\otimes X = \left[\underline{X}, \bar{X}\right]$, $\otimes X$ is a grey number with insufficient and/or uncertain information.

Let there be two sets of grey numbers denoted by $\otimes X_1 = \left[\underline{X_1}, \overline{X_1}\right]$ and $\otimes X_2 = \left[\underline{X_2}, \overline{X_2}\right]$. The basic mathematical operations for these two sets of grey numbers are listed below.

$$\otimes X_1 + \otimes X_2 = \left[\underline{X_1} + \underline{X_2}, \overline{X_1} + \overline{X_2}\right] \tag{1}$$

$$\otimes X_1 - \otimes X_2 = \left[\underline{X_1} - \overline{X_2}, \overline{X_1} - \underline{X_2}\right] \tag{2}$$

$$\begin{aligned} \otimes X_1{}^{*} \otimes X_2 = \Big[& min\left(\underline{X_1 X_2}, \overline{X_1 X_2}, \underline{X_1}\overline{X_2}, \overline{X_1}\underline{X_2}\right), \\ & max\left(\underline{X_1 X_2}, \overline{X_1 X_2}, \underline{X_1}\overline{X_2}, \overline{X_1}\underline{X_2}\right)\Big] \end{aligned} \tag{3}$$

$$\otimes X_1 : \otimes X_2 = \left[\underline{X_1}, \overline{X_1}\right] * \left[\frac{1}{\overline{X_2}}, \frac{1}{\underline{X_2}}\right] \tag{4}$$

$$k^{*} \otimes X_1 = \left[k\underline{X_1}, k\overline{X_1}\right], k \epsilon R \tag{5}$$

$$\otimes X_1{}^{-1} = \left[\frac{1}{\overline{X_1}}, \frac{1}{\underline{X_1}}\right] \tag{6}$$

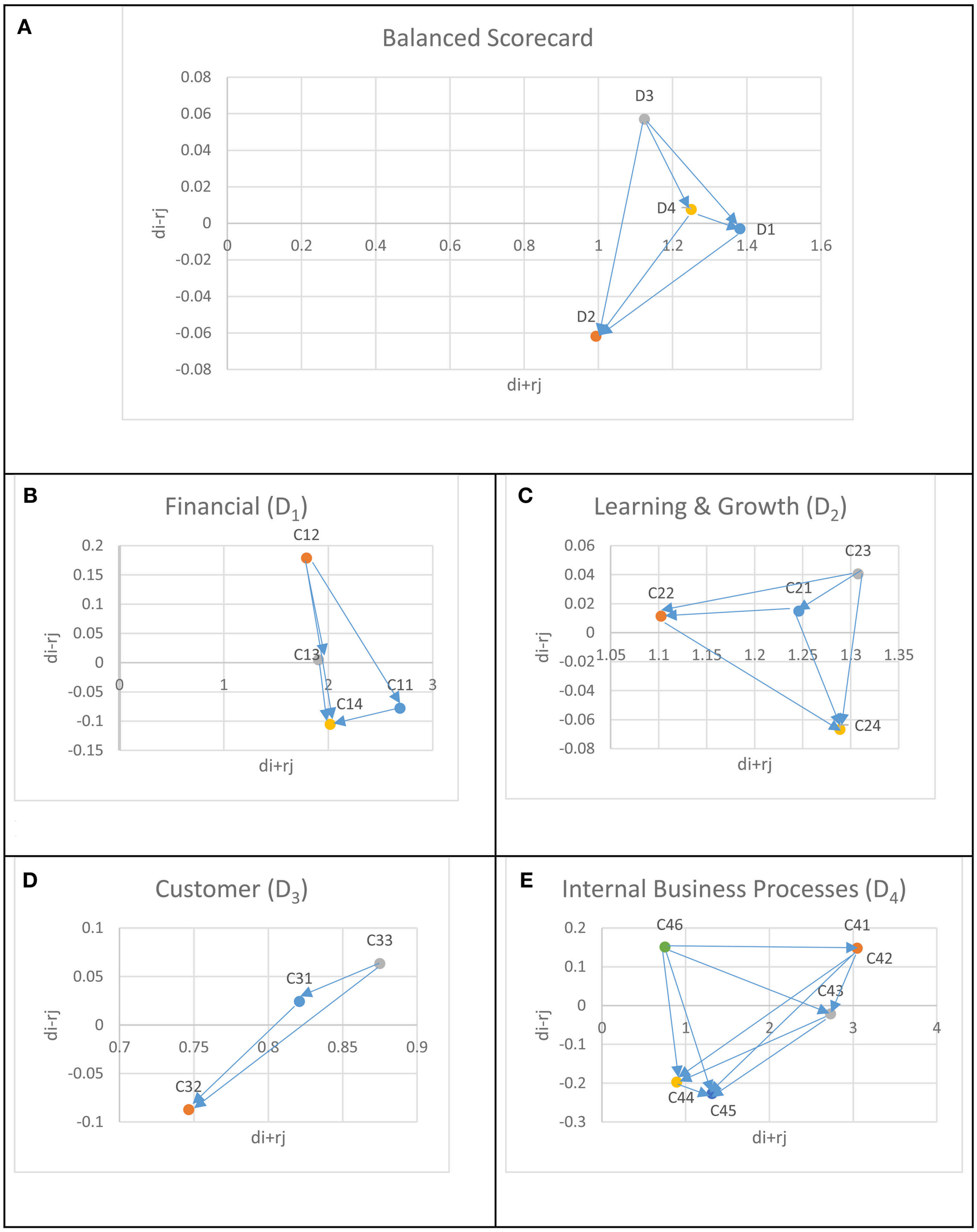

FIGURE 2 | The network relation map. **(A)** The network relation map of the BSC dimensions. **(B)** The network relation map of the criteria under D1. **(C)** The network relation map of the criteria under D2. **(D)** The network relation map of the criteria under D3. **(E)** The network relation map of the criteria under D4.

In order to deal with the problems in a grey environment, an effective whitenization (grey aggregation) method is required. Opricovic et al. (44) developed Converting Fuzzy Data into Crisp Scores (CFCS) method to cope with the uncertainty and vagueness in multi-criteria decision problems. CFCS is designed to distinguish between two fuzzy numbers with the same crisp value obtained by the Centroid (center of gravity) method independent of the shape of the fuzzy numbers (34). The steps of the modified CFCS method utilized in this research are provided below.

Let $\otimes x_{ij}^{p} = \left[\underline{x}_{ij}^{p}, \overline{x}_{ij}^{p}\right]$ indicate the grey assessment of evaluator, p (decision maker), that will evaluate the influence of criterion i on criterion j. Then the following

Step 1: Normalization

$$\tilde{\overline{x}}_{ij}^{p} = \left[\overline{x}_{ij}^{p} - min_j \overline{x}_{ij}^{p}\right] / \Delta_{\min}^{\max} \quad (7)$$

$$\tilde{\underline{x}}_{ij}^{p} = \left[\underline{x}_{ij}^{p} - min_j \underline{x}_{ij}^{p}\right] / \Delta_{\min}^{\max} \quad (8)$$

where

$$\Delta_{\min}^{\max} = max_j \overline{x_{ij}^{p}} - min_j \tag{9}$$

Step 2: Determination of a total normalized crisp value

$$Y_{ij}^{p} = \frac{(\underline{\widetilde{x_{ij}^{p}}}(1 - \underline{\widetilde{x_{ij}^{p}}}) + (\overline{\widetilde{x_{ij}^{p}}} * \overline{\widetilde{x_{ij}^{p}}}))}{(1 - \underline{\widetilde{x_{ij}^{p}}} + \overline{\widetilde{x_{ij}^{p}}})} \tag{10}$$

Step 3: Calculate crisp values

$$z_{ij}^{p} = min_j x_{ij}^{p} + Y_{ij}^{p} \Delta_{\min}^{\max} \tag{11}$$

The DEMATEL Based ANP (DANP) Method

The DANP is a novel approach that combines the original DEMATEL and ANP methods to utilize total relation matrix for the criteria and the clusters, viz., the BSC dimensions in this study, and to build a network relation map (NRM) of the decision model. Based on the network relation map, the influential relationships are then obtained (26). The basic steps of the DANP approach are provided as follows:

- Generate the direct relation matrix

The initial step in this process is to obtain the decision maker assessments regarding the direct influence among the criteria. These assessments are represented as grey numbers and can be represented by one of the following five levels; "no influence," "low influence," "medium influence," "high influence," and "very high influence," Here, the initial direct-relation matrix $\boldsymbol{A}$ is an $n \times n$ matrix where a_{ij} indicates the degree that the criterion i affects the criterion j and $A = [a_{ij}]_{nxn}$.

- Normalize the direct relation matrix

The normalized direct-relation matrix $X = [x_{ij}]_{nxn}$ can be obtained through

$$X = A/s \tag{12}$$

$$where\ s = max\left[max \sum_{i=1}^{n} a_{ij}, max \sum_{j=1}^{n} a_{ij}\right]. \tag{13}$$

Here, the normalized initial direct-relation matrix is obtained via Equation (12), and the $\boldsymbol{s}$ value representing the maximum values of the sums of all the rows and the sums of all the columns is calculated via Equation (13).

- Obtain the total relation matrix

The total relation matrix $\boldsymbol{T}=[t_{ij}]_{nxn}$ can be obtained by utilizing Equation (14) where $\boldsymbol{I}$ is the identity matrix:

$$T = X + X^2 + X^3 + \ldots + X^k = \sum_{k=1}^{\infty} X^k = X(I - X)^{-1}. \tag{14}$$

Furthermore, the method utilizes the sums of each row and column of the matrix T to build the NRM.

$$d_i = (r_i)_{nx1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1}. \tag{15}$$

$$r_j = (c_j)_{nx1} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn}. \tag{16}$$

Here, Equation (15) represents the row sum of the ith row of matrix T and shows the sum of direct and indirect effects of criterion i on the other criteria. Similarly, Equation (16) represents the sum of the jth column of matrix T and shows the sum of direct and indirect effects that criterion j has received from the other criteria. Furthermore, $(d+r)$ indicates the importance of the criterion. Here, if $(d–r)$ results in positive value it is implied that the criterion has an effect on others. Similarly, when $(d–r)$ obtains a negative value then the criterion is affected by the others.

- Formation of an unweighted super-matrix

The weighted super-matrix is obtained by dividing each element in a column by the number of clusters with each cluster having equal weights. However, the equal weight assumption for each cluster is not always feasible due to the different degrees of influence among the criteria (45). In order to relax this unrealistic assumption, two different total influence matrices are then utilized. The first one, $T_c = \left[t_c^{ij}\right]_{nxn}$ pertains to m criteria, while the second one, $T_D = \left[t_D^{ij}\right]_{nxn}$ is devoted to n dimensions, i.e., clusters, as shown in Equations (17) and (18).

$$T_C = \begin{array}{cc} & \begin{array}{cccc} D_1 & D_2 & \cdots & D_n \\ c_{11}\ldots c_{1m1} & c_{21}\ldots c_{2m2} & \cdots & c_{n1}\ldots c_{nmn} \end{array} \\ \begin{array}{cc} D_1 & \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m1} \end{array} \\ D_2 & \begin{array}{c} c_{21} \\ c_{22} \\ \vdots \\ c_{2m2} \end{array} \\ \vdots & \vdots \\ D_n & \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nmn} \end{array} \end{array} & \begin{bmatrix} T_c^{11} & T_c^{12} & \cdots & T_c^{1n} \\ T_c^{21} & T_c^{22} & \cdots & T_c^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ T_c^{n1} & T_c^{n2} & \cdots & T_c^{nn} \end{bmatrix} \end{array} \tag{17}$$

$$T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{in} \\ \vdots & & \vdots & & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix} \tag{18}$$

- Normalize the total relation and total influence matrices

The normalized total relation matrix of criteria T_C^{nor} is computed by dividing the sum of each row in each sub-matrix. For instance, the normalized sub-matrix T_C^{nor12} is calculated as in Equation (19).

$$T_C^{12} = \begin{array}{c} \\ c_{11} \\ \vdots \\ c_{1j} \\ \vdots \\ \vdots \\ c_{1m1} \end{array} \begin{array}{c} \begin{array}{cccc} c_{21} & c_{2j} & & c_{2m2} \end{array} \\ \begin{bmatrix} t_{11}^{12} & t_{1j}^{12} & \cdots & t_{1m2}^{12} \\ \\ t_{i1}^{12} & t_{ij}^{12} & \cdots & t_{im2}^{12} \\ \\ \vdots & \vdots & \ddots & \vdots \\ \\ t_{mi1}^{12} & t_{mij}^{12} & \cdots & t_{m1m2}^{12} \end{bmatrix} \end{array} \begin{array}{l} \\ \rightarrow \quad r_1^{12} = \sum_{j=1}^{m2} t_{1j}^{12} \\ \\ \rightarrow \quad r_i^{12} = \sum_{j=1}^{m2} t_{1j}^{12} \\ \\ \vdots \qquad \vdots \\ \\ \rightarrow \quad r_{m1}^{12} = \sum_{j=1}^{m2} t_{mij}^{12} \end{array} \tag{19}$$

where r_i^{12} represents the sum of each row in the sub matrix T_C^{12}. Then T_C^{nor12} is obtained as shown in Equation (20).

$$T_C^{nor12} = \begin{bmatrix} t_{11}^{12}/r_1^{12} & t_{1j}^{12}/r_1^{12} & \cdots & t_{1m2}^{12}/r_1^{12} \\ t_{i1}^{12}/r_i^{12} & t_{ij}^{12}/r_i^{12} & \cdots & t_{im2}^{12}/r_i^{12} \\ \vdots & \vdots & \ddots & \vdots \\ t_{mi1}^{12}/r_{m1}^{12} & t_{mij}^{12}/r_{m1}^{12} & \cdots & t_{m1m2}^{12}/r_{m1}^{12} \end{bmatrix} \tag{20}$$

Similar to T_C^{nor}, the normalized total influential matrix for clusters T_D^{nor} is formed as shown in equation (21).

$$T_D^{nor} = \begin{bmatrix} t_D^{11}/t_D^1 & \cdots & t_D^{1j}/t_D^1 & \cdots & t_D^{1n}/t_D^1 \\ \vdots & & \vdots & & \vdots \\ t_D^{i1}/t_D^i & \cdots & t_D^{ij}/t_D^i & \cdots & t_D^{in}/t_D^i \\ \vdots & & \vdots & & \vdots \\ t_D^{n1}/t_D^i & \cdots & t_D^{nj}//t_D^i & \cdots & t_D^{nn}/t_D^i \end{bmatrix} = \begin{bmatrix} t_D^{nor11} & \cdots & t_D^{nor1j} & \cdots & t_D^{nor1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{nori1} & \cdots & t_D^{norij} & \cdots & t_D^{norin} \\ \vdots & & \vdots & & \vdots \\ t_D^{norn1} & \cdots & t_D^{nornj} & \cdots & t_D^{nornn} \end{bmatrix} \tag{21}$$

where the sum of each cluster is defined as $t_D^i = \sum_{j=1}^{n} t_D^{ij}$.

- Build a weighted super-matrix

The unweighted super-matrix U_C is the matrix transposed from the normalized total relation matrix for the criteria T_C^{nor} as shown in Equation (22).

$$U_C = (T_C^{nor})' = \begin{array}{cc} & \begin{array}{cccc} D_1 & D_2 & \cdots & D_n \\ c_{11}\ldots c_{1m1} & c_{21}\ldots c_{2m2} & \cdots & c_{n1}\ldots c_{nmn} \end{array} \\ \begin{array}{cc} D_1 & \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m1} \end{array} \\ D_2 & \begin{array}{c} c_{21} \\ c_{22} \\ \vdots \\ c_{2m2} \end{array} \\ \vdots & \vdots \\ D_n & \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nmn} \end{array} \end{array} & \begin{bmatrix} U^{11} & U^{i1} & \cdots & U^{n1} \\ U^{1j} & U^{ij} & \cdots & U^{nj} \\ \vdots & \vdots & \ddots & \vdots \\ U^{11} & U^{in} & \cdots & U^{nn} \end{bmatrix} \end{array} \tag{22}$$

The weighted super-matrix W is obtained by incorporating the unweighted super-matrix U_C and the normalized total influential matrix for clusters T_D^{nor} is shown in Equation (23):

$$W = \begin{bmatrix} t_D^{nor11} x U^{11} & \cdots & t_D^{nori1} x U^{i1} & \cdots & t_D^{nor1n} x U^{n1} \\ \vdots & & \vdots & & \vdots \\ t_D^{nor1j} x U^{1j} & \cdots & t_D^{norij} x U^{ij} & \cdots & t_D^{norinj} x U^{nj} \\ \vdots & & \vdots & & \vdots \\ t_D^{nor1n} x U^{1n} & \cdots & t_D^{nornj} x U^{in} & \cdots & t_D^{nornn} x U^{nn} \end{bmatrix} \tag{23}$$

- Limit the weighted super-matrix to obtain criteria weights

In order to obtain the final influential criteria weights, the weighted super-matrix W is raised to a sufficiently large power z until it converges and becomes a long-term stable super-matrix:

$$\lim_{s \to \infty} (W)^z \tag{24}$$

A FOOD INDUSTRY CASE STUDY

The case study is conducted in a U.S. based fast food restaurant company that owns several franchise retail stores in the northeast region. The company management is in the process of introducing sustainability into their performance evaluation

TABLE 1 | Criteria and their definitions.

Dimensions	Criteria	Definition	
Financial (D_1)	C_{11}	Weekly sales	Total weekly sales in each store
	C_{12}	Weekly expenses	Total weekly expenses in each store
	C_{13}	Total number of carry-out orders	Total number of weekly carry-out orders in each store
	C_{14}.	Total number of delivery orders	Total number of weekly delivery orders in each store
arning & Growth (D_2)	C_{21}	Food safety initiatives	A measure related to increasing food safety in each store
	C_{22}	Operational safety initiatives	A measure related to increasing safety both in-store and in delivery operations
	C_{23}	Quality and development initiatives	A measure related to building skills and capabilities for higher product and service quality in each store
	C_{24}	Sustainable development initiatives	A measure related to building skills and capabilities in sustainability applications integrated into the routine workflow in each store
Customer (D_3)	C_{31}	Number of customer complaints	Total number of weekly customer complaints in each store
	C_{32}	Green image of the store	A measure related to the overall green image from a customer view in each store
	C_{33}	Social responsibility image of the store	A measure related to the overall social responsibility image from a customer view in each store
Internal Business Processes (D_4)	C_{41}	On-time delivery ratio	The ratio of the amount of orders delivered no later than the estimated time
	C_{42}	Out to door time ratio	The ratio of the amount of orders completed in the store no later than the estimated time
	C_{43}	Resource utilization ratio	The ratio of the utilization of in-store personnel, delivery personnel, materials, and other resources in the store
	C_{44}	Forecast accuracy ratio of food inventory	The ratio of forecasting accuracy of the raw food amount ordered weekly
	C_{45}	Utilization of local food suppliers	The utilization ratio of local food suppliers in the neighborhood
	C_{46}	Rate of proper recycling and waste disposal	The ratio of ensuring safety and protecting the environment through proper recycling and disposal of wastes

system and is investigating how these perspectives interact with each other. With this motivation, this study applies the proposed methodology using the data collected from the subject matter experts in the company.

Criteria Definition

Based on the balanced scorecard approach, the literature review, expert opinions, and interviews with the upper level management of the company, the performance evaluation criteria are determined. The criteria and their respective definitions are provided in **Table 1**.

Application of the Proposed Model

As mentioned in the proposed methodology section, Balanced Scorecard-Based Grey-DANP approach is applied to determine the global weights of the dimensions in BSC and the criteria. The decision makers used linguistic terms to assess the influences between the criteria. The assessment scale used in Grey-DANP is provided in **Table 2**.

The direct relation matrix is formed according to franchisee and supervisors point of view and demonstrated in **Table 3**.

The whitened assessments in the direct relation matrix are obtained via utilizing modified-CFCS method from Equations (7–11). Following this, the total relation matrix is obtained by utilizing Equations (12–14). The results are provided in the Appendix A in Tables A1,A2. Furthermore, the total influences given and received on the criteria along with the dimensions can be calculated using Equations (15, 16) as shown in **Table 4**.

TABLE 2 | The grey linguistic scale for the assessments.

Linguistic terms	Grey Numbers
No influence (N)	[0, 0]
Low influence (L)	[0, 0.25]
Medium influence (M)	[0.25, 0.50]
High influence (H)	[0.50, 0.75]
Very high influence (VH)	[0.75, 1.00]

Thus, the influence diagram, a.k.a. the network relation map (NRM) from the DEMATEL method can be obtained as illustrated in **Figure 2**.

According to the results of the total relation matrix provided in Table A2, the influential weight of each criterion is obtained via the ANP algorithm. The normalized super-matrix T_C^{nor} is built by employing Equations (17–20). An unweighted super-matrix U_C can be derived by transposing the normalized matrix as shown in Equation (22). The weights of the BSC dimensions (clusters) can be derived from the improved DANP method without employing further surveys as shown in Equation (21) instead of

TABLE 3 | The linguistic scale direct-relation matrix for the criteria.

Criteria	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}
C_{11}	N	H	VH	VH	N	N	N	N	N	N	N	VH	VH	VH	H	M	N
C_{12}	VH	N	H	H	L	L	L	L	N	M	H	H	H	N	N	L	N
C_{13}	VH	M	N	N	L	L	L	L	N	L	L	VH	VH	H	L	H	N
C_{14}	VH	M	N	N	L	L	L	L	N	L	L	VH	VH	H	L	H	N
C_{21}	N	M	N	N	N	M	H	H	H	M	M	N	N	N	M	M	M
C_{22}	N	M	N	N	M	N	H	H	M	M	M	N	N	N	L	M	L
C_{23}	VH	M	N	N	H	H	N	H	H	M	M	N	N	N	L	L	L
C_{24}	N	L	N	N	H	H	H	N	L	M	M	N	N	L	L	M	M
C_{31}	N	N	H	H	H	H	H	H	N	L	L	VH	VH	H	M	N	L
C_{32}	N	L	L	L	M	M	M	H	N	N	H	N	N	N	L	L	VH
C_{33}	N	L	L	L	H	M	H	H	L	VH	N	N	N	N	L	VH	VH
C_{41}	VH	M	VH	VH	N	N	N	N	VH	N	N	N	VH	VH	L	M	N
C_{42}	VH	M	VH	VH	N	N	N	N	VH	N	N	VH	N	VH	L	M	N
C_{43}	VH	M	N	H	N	N	N	N	VH	M	N	VH	VH	N	L	L	L
C_{44}	L	H	N	N	H	M	L	L	L	L	L	N	N	M	N	N	L
C_{45}	L	M	L	L	H	L	L	H	L	L	VH	N	N	M	H	N	N
C_{46}	N	L	N	N	L	L	M	VH	VH	VH	VH	N	N	N	N	N	N

TABLE 4 | The sum of influences provided and received on the criteria and dimensions.

Dimensions/Criteria	d_i	r_j	$d_i + r_j$	$d_i - r_j$	
D_1	Financial	0.689	0.692	1.381	−0.003
C_{11}	Weekly sales	1.305	1.383	2.687	−0.078
C_{12}	Weekly expenses	0.985	0.806	1.791	0.179
C_{13}	Total number of carry-out orders	0.955	0.951	1.906	0.005
C_{14}	Total number of delivery orders	0.955	1.061	2.017	−0.106
D_2	Learning & Growth	0.466	0.528	0.994	−0.062
C_{21}	Food safety initiatives	0.630	0.615	1.246	0.015
C_{22}	Operational safety initiatives	0.557	0.546	1.102	0.011
C_{23}	Quality and development initiatives	0.674	0.634	1.308	0.040
C_{24}	Sustainable development initiatives	0.611	0.678	1.289	−0.067
D_3	Customer	0.591	0.534	1.124	0.057
C_{31}	Number of customer complaints	0.423	0.398	0.821	0.024
C_{32}	Green image of the store	0.330	0.417	0.746	−0.087
C_{33}	Social responsibility image of the store	0.469	0.406	0.875	0.063
D_4	Internal Business Processes	0.629	0.621	1.251	0.008
C_{41}	On-time delivery ratio	1.598	1.450	3.048	0.148
C_{42}	Out to door time ratio	1.598	1.450	3.048	0.148
C_{43}	Resource utilization ratio	1.355	1.376	2.731	−0.022
C_{44}	Forecast accuracy ratio of food inventory	0.347	0.545	0.892	−0.197
C_{45}	Utilization of local food suppliers	0.544	0.771	1.315	−0.227
C_{46}	Rate of proper recycling and waste disposal	0.452	0.301	0.753	0.151

using additional pairwise comparisons amongst dimensions (45). Therefore, the weighted super-matrix W can be obtained through Equation (23). The final influential weights of each criterion can then be obtained by limiting the power of the weighted super-matrix until it converges into a steady state as shown in Equation (24). Resulting matrices are provided in Appendix A from Tables A3–A5, respectively. The global weights of the criteria (Table A5) can be obtained from the DANP method. Using these results, the local weight of each criterion and dimension can also be derived accordingly. The global and local weights along with the rankings of the criteria and BSC dimensions are provided in **Table 5**.

TABLE 5 | The influential weights of the BSC dimensions and the criteria.

Dimension	Local weight	Ranking	Criteria	Local weight	Global weight	Ranking
D_1	0.278	2	C11	0.309	0.086	1
			C12	0.232	0.065	7
			C13	0.214	0.060	8
			C14	0.245	0.068	6
D_2	0.199	3	C21	0.270	0.054	11
			C22	0.213	0.042	14
			C23	0.239	0.047	12
			C24	0.278	0.055	10
D_3	0.159	4	C31	0.445	0.071	5
			C32	0.259	0.041	15
			C33	0.296	0.047	13
D_4	0.364	1	C41	0.227	0.083	2
			C42	0.227	0.083	3
			C43	0.203	0.074	4
			C44	0.099	0.036	16
			C45	0.154	0.056	9
			C46	0.090	0.033	17

CONCLUSIONS AND DISCUSSION

Integrating environmental and social sustainability into business processes is becoming crucial to remain competitive in the current business environment. However, contemporary literature focusing on food service industry performance measurement is solely based on economic indicators and falls short in integrating these considerations into the evaluation process. Aiming at filling this gap, this study proposed an integrated approach combining social, environmental, and economic aspects together in the performance evaluation system of a fast food restaurant company. A Balanced Scorecard based Grey-DANP approach is applied to reveal the influences among the evaluation criteria and rank them with respect to their importance weights. A fast food restaurant company is selected as a case study to demonstrate the applicability of the approach.

Besides being the earliest study in combining Balanced Scorecard and Grey-DANP approaches in integrating sustainability aspects into performance evaluation framework, this research identifies the environmental and social performance measures a food store could utilize. Previously published studies consider the sustainability measures independent from one another and hence, mostly avoid the inter-influences which are not compatible with real world applications. Moreover, this study highlights that avoiding these criteria interactions may result in misleading criteria weights. The proposed approach revealed that although financial measures had higher importance values, environmental, and social measures also had significant influence. For instance, as it can be observed from **Table 4** and **Figure 2A**, Financial Perspective (D1) has stronger relationships with the remaining BSC dimensions while Customer Perspective (D3) has the highest influence on others. As far as the evaluation criteria under the BSC perspectives are concerned, similar findings can be observed from **Figure 2** and **Table 4**. The final ranking of the evaluation criteria with respect to their importance level is provided in **Table 5**. In terms of managerial implications, the findings of the proposed approach can provide some insight that can guide the company management to improve the store performance based on the criteria that have significant influence on the performance (18). In the future, the results of this study can be utilized in a performance evaluation technique (e.g., TOPSIS) with numerical data collected from the stores. This data can then be used to rank the stores with respect to their individual performances. The criteria set can be expanded to include additional environmental and social measures such as reduction in water and energy consumption in each store. Furthermore, for comparison purposes, a conventional AHP based study could be conducted to obtain the criteria weights in the same case study.

AUTHOR CONTRIBUTIONS

GD and EK devised the project, the main conceptual ideas and proof outline. GD worked out almost all of the technical details, and performed the numerical calculations for the case study. MT provided the data and information regarding the case study. EK and KR verified the analytical methods. All authors provided critical feedback and helped shape the research and analysis. All authors discussed the results and contributed to the final manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2018.00065/full#supplementary-material

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When Utilitarian Claims Backfire: Advertising Content and the Uptake of Insects as Food

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A key challenge for climate change mitigation on the consumer side is to break habits that excessively lead to carbon emission. One of the culturally most robust human routines is the heavy reliance of the Western societies on conventional meat sources such as beef, pork, and poultry, which were recently accused of causing particularly high climate costs. In this light, the UN (FAO) has suggested the increasing use of insects as an alternative source of animal protein intended for human diets. Yet, insects have not reached the mainstream of Western cuisine. Currently, a frequent promotion strategy of insects is to highlight the Utilitarian benefits associated with their consumption (e.g., with respect to the environment or one's health). The present research addresses the efficacy of such claims in a consumer research study involving 180 participants recruited from the general population in Germany. Arguing based on social-cognitive research in the area of moral and environmental psychology, we hypothesized and found that a focus on beneficial, but temporally distant motives (e.g., health)—counterintuitively—decreases consumption in comparison to immediate, hedonic advertisements (e.g., tasty). Furthermore, our study provides process evidence suggesting pretrial expectations induced by a particular claim mediate the relationship between claims and consumption. Thus, the present research not only refutes a state-of-the-art approach in the promotion of insects as food, but also provides an alternative approach and process evidence by integrating psychological factors.

Keywords: entomophagy, marketing, consumer behavior, sustainable food, disgust

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INTRODUCTION

The increasing concern about the impact of our modern lifestyles on the earth's ecosystem has led to immense efforts to address climate change. Globally, food production accounts for about a quarter of all anthropogenic greenhouse gas emissions (1), and the upward trend is expected to continue. Research on climate cost of conventional foods emphasizes the problematically high level of conventional meat intake (2). Insect-based consumption has been suggested as a more sustainable (e.g., less carbon dioxide emissions and lower water footprint) and healthy (high in protein, fats, minerals, and vitamins) way of consuming animal protein (3–5), with high economic value (6). In their report, the United Nations (7), systematically compare nutrients and climate costs of various insect species against conventional meat sources and conclude that insects are indeed a viable alternative source of animal protein.

The rising interest in entomophagy (i.e., insect consumption by humans) results not only from the increased attention paid to anthropogenic climate change but also from recent advances in agricultural technology and food safety, which make insects a viable option for industrial and private production. This enables innovators from top-level cuisine just like several young companies to enter the market for insects as food, offering various consumer products ranging from luxurious options to mass-market alternatives. However, despite these advances and the environmental benefits, insects are rarely eaten in Western countries and the confrontation with insect-based food often evokes skepticism and disgust (8). Disgust is primarily a result of social and cultural learning but also has trait-like qualities, namely the general tendency to become disgusted (9). Both learning processes and disgust sensitivity serve the important function of preventing people from consuming rotten or toxic food (10). Moreover, disgust can be easily generalized, leading associated items of a detestable object to become disgusting themselves (10). Concerning entomophagy, this means that Westeners may have a stereotyped knowledge of insects and other species, and the association of some of those animals with decaying matter and feces could have led to psychological contamination of the entire category (11). However, this does not help to explain why seafood such as crawfish is seen as something "delicious" and regularly enters Westerners' dinner plates whereas insects are seen as something disgusting. Confidence that large-scale behavioral change in favor of insect-based diets is possible may come, for example, from the historical development of the lobster as a luxury product. Once seen as excessive "garbage" in New England (USA), people quip that regulation even existed that lobsters should not be fed to prisoners too frequently. Not only is lobster nowadays a highly rated luxury product, but it is also a key marketing content of New England as a tourist region and hardly an affordable food option for middle-class consumers on a daily base.

Despite the increasing interest in and the great potential of insects as food, scientific knowledge about consumer behavior in the field of entomophagy is largely lacking and has so far primarily focused on correlational studies or hypothetical vignettes [(12), c.f. (13)]. The main aim of the present research is to address this lacuna and to show effective strategies associated with a higher inclination to rely on this source of environmentally friendly and healthy source of animal protein. But how can consumers be approached when one tries to convince them to eat insects? The "as is" strategy of many supporters of entomophagy is to highlight the *environmental* and *health* benefits. This research has placed a high emphasis on the effectiveness of environmental framings on consumer choices, especially in comparison to economic incentives [e.g., (14)]. For instance, this research shows that appealing to environmental motives may outperform appeals to monetary incentives when motivating green behaviors of consumers such as maintaining sufficient tire pressure on one's car. Besides this evidence, a large class of consumer psychological work addresses the effect of environmental or social "labels" (e.g., Fair Trade, eco-friendly) on product judgments [e.g., (15)]. The key result from this research provides robust converging evidence that consumers respond positively to such claims, especially in the domains of "green behaviors" [e.g., (16)]. In addition, research also seems to suggest that "halo effects" of green foods spill over to ratings of healthiness (17, 18). Drawing on this widely known research alone, it is no wonder that many promoters of entomophagy routinely highlight the environmental and health benefits of eating insects, which may seem as the natural candidate for marketing and advertisement campaigns wanting to raise the interest in and willingness to eat insects. And in fact, a plethora of work dealing with entomophagy, not only in the UN FAO report, but also in the popular media ranging from TV documentaries (19) to newspaper articles (20), frequently emphasizes the environmental benefits or the high protein value of insect-based diets. Although these claims are correct and such rational persuading strategies have led to an increase in the awareness of entomophagy benefits, they have barely heightened Westeners' willingness to consume insects (21).

A first skeptical view on the efficacy of Utilitarian claims stems from basic research that links disgust to *executive functions* (22, 23). Executive functions are a set of cognitive processes that are necessary for the cognitive control of behavior. Recent research in environmental behavior calls for a change of the overarching analytical framework to include the role of cognitive control into environmental research and campaigns (24). The key argument is that environmental behavior requires cognitive control by design. Typical environmental-friendly behavior requires foregoing immediate and salient pleasures (e.g., flying to a tropical island, using a car instead of a bike when commuting to work in the rain, not eating excessive amounts of meat, etc.), while the benefits (less CO_2 emission, more sustainability of resources, etc.) are temporally distant. Also, insect consumption is currently framed as an experience with hardly any immediate rewards, but instead, with long-term utility such as being healthy or being environmentally friendly. Thus, even if consumers were in principle motivated to eat insects for environmental reasons, this process would require certain levels of cognitive control. However, research has linked disgust to a decrease in inhibitory control (25), which is required to make such long-term, goal-oriented decisions. This research suggests that disgusting distracters consume *more* attentional resources and therefore *impair* subsequent inhibitory control to a greater extent than non-disgusting distractors. This would implicate that a decrease in feelings of disgust by hedonic persuasion strategies may also be crucial in order to help individuals to exert the self-control needed for consuming insects for utilitarian reasons. In other words: If insects are perceived as disgusting, as much research suggests (11), highlighting the long-term benefits may not lead a higher willingness-to-consume.

Another explanation for the lack of success of rational persuasion strategies may lie in the fact that attitudes are not only based on rational thoughts and beliefs but also on emotions and feelings. Several researchers [e.g., (26, 27)] have shown that if an attitude is relatively more cognitive or affective in nature has important implications: Attitudes that are based on emotions can generally be changed more effectively with emotional messages than with more cognitive and rational claims. As discussed earlier, central to the aversion toward insects is the feeling of disgust that it evokes in consumers. From the findings of Fabrigar and Petty (26), it directly follows that people's low willingness to eat insects could be influenced more effectively by emotional or hedonic (i.e., insects are tasty) compared to Utilitarian arguments (i.e., our planet needs to be protected). Moreover, research has demonstrated that inducing positive affect in turn can increase participants' ability to make Utilitarian judgements (28). Applying this argument to the present context, participants may be more likely to respond to Utilitarian claims when positive feelings for entomophagy have already been developed. Research on attitudes and ambivalence provides a possible explanation for this effect: People can experience both positive and negative emotions toward an attitude object, which leads to an inner conflict that is particularly apparent when it comes to attitude-relevant decision-making (29). The advantage of this ambivalence is, that it results in enhanced information processing in order to resolve the inner tension (30), and thereby people are more susceptible to new information. Hence, hedonic advertisement may - due to positive change in attitude and potentially stronger information processing - lead to enhanced willingness to try insects.

Another crucial channel through which preference development works is pre-trial product expectations. Consumer research has suggested that much of our judgment happens as a "top-down" approach (31). Typically, consumers form expectations about the quality or other intrinsic, but a-priori unknown product characteristics (taste, smell, overall liking, etc.) and, subsequently tend to adhere to their expectation. Because of the strong relationship between pre-trial expectations and product preference, it may prove particularly useful to aim at expectations. As consistency is one of the central drivers of judgment and decision making (32), it is not surprising that many marketing actions (e.g., pricing decisions, packaging, branding, advertisement content) actually aim at raising product expectations, which then easily translate into corresponding preference judgments due to consistency motives by the consumer. Therefore, one suitable channel through which the willingness to eat an insect may be influenced is expectations. Much research supports this process in other food domains. For instance, a study found that knowing before (hence, relevant for expectation building) consumption that a beer is laced with vinegar is detrimental for taste reportings, but learning after tasting does not bias expectations and therefore results in higher taste ratings (33). Furthermore, neuroscientific studies support this reasoning by showing that knowledge about high vs. low prices in wine-tastings leads to brain reactions that already predispose a respective judgment (34). With regard to our study, this means, that the increase in willingness to try insect-based products by hedonic persuasion messages may be mediated by enhanced product expectations (see **Figure 1**).

To sum up, our central hypothesis is that disgust-based aversions to insects as food are best counterstruck with appeals to hedonic experience rather than by Utilitarian arguments that speak to long-term preferences such as a sustainability of the planet or the healthiness. Moreover, we hypothesize that pre-trial quality expectations mediate this effect. Also, we control for individual differences in disgust sensitivity as well as gender differences, two variables previously associated with insect-consumption (see **Figure 1**).

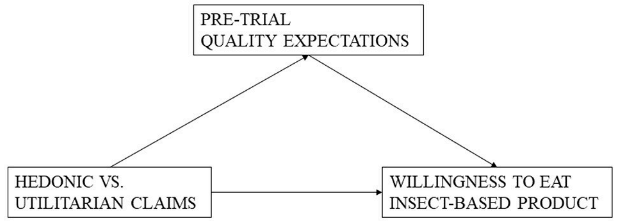

FIGURE 1 | Mediation Model. Link between hedonic persuasion messages and willingness to try inset-based products mediated by enhanced product expectations.

METHODS AND PROCEDURE

Participants and Recruiting Procedure

Our experiment was run with a total of 180 volunteer participants (M_{age} = 24.7, SD_{age} = 8.13, 63 percent females) ranging between 18 and 72 years. The large majority (N = 158) was of German nationality and well-educated (115 participants had graduated from high school, 32 from university). The participants had different occupational backgrounds. All were recruited on a centrally located and highly frequented square in Cologne, Germany, to capture a suitable cross-section of the city's population. None of the participants was directly incentivized for eating insect-based foods, but instead, all of them received a flat monetary compensation (€5.00, for about 15–20 min) for their participation in a consumer study. Participants were held unaware during recruiting that the study involved an opportunity to eat an insect. Instead, they were merely recruited for a consumer study focusing on "new products." As our interest was in the general willingness to consume an insect, this recruiting strategy left our sample unbiased in a sense that people with a particular interest or particularly high levels of disgust could not self-select into or opt-out of the study at this point. Randomization checks in terms of gender, age, previous consumption, and individual difference in disgust sensitivity result in the fact that no important variable was overrepresented in a particular experimental group (gender: $p = 0.958$, age: $p = 0.616$, previous insect consumption: $p = 0.145$, disgust sensitivity: $p = 0.693$).

Participants gave written informed consent and learnt about benefits and risks of the study. The local ethics committee approved the study without a protocol number and further ethical approval was not required. Participants also received the information that people with certain allergic reactions (seafood, gluten, lactose, and nuts/chocolate) as well as pregnant women could not participate in the study due to the novelty of the food and lacking research into potentially adverse effects of insects as food. If a person announced to be allergic or pregnant, s/he received the monetary compensation and was dismissed from the study. People reporting allergic reactions were very rare. Our stopping rule for the sample size was to recruit another participant in case someone reported allergies or pregnancy so that the final samples would be exactly 180 participants (i.e., ∼30 per advertisement, therefore, ∼60 in the Utilitarian condition and ∼120 in the hedonic condition). The study followed all rules of the Declaration of Helsinki. The study was conducted in German.

Experimental Procedure

Upon arrival at the laboratory, participants received oral and written instructions. After consenting, participants worked through a questionnaire that first gave general information about insects as food. The key experimental manipulation was the presentation of an information sheet. In that sheet, participants were confronted with an advertisement flyer of a start-up company planning to enter the entomophagy market. The key sentence on the advertisement was manipulated and always included the statement: "Eating meat has never been so [. . .]." The sentence concluded with one of two types of manipulations, tapping into hedonic reason (dummy coded as 0) vs. Utilitarian reasoning (dummy coded as 1). In the Utilitarian information flyers, the sentence concluded with a random presentation of the words "good for the body" (i.e., healthy), "good for the environment" (i.e., environmentally friendly), or "exquisite" (i.e., highlighting status-oriented consumption). These are the main Utilitarian reasons currently employed by promoters of entomophagy. Tapping into hedonic claims, we used various alternative randomly presented words (delicious, exotic, or trendy).

Participants were asked to engage with the advertisement by writing a short statement about what they saw and what they thought about the informational flyer. The reason for this was that we thus could assure that participants perceive the information and spend some time thinking about the advertisement. After completing this task and some additional questions about their consumption habits (frequency of insect, beef, poultry, and vegetarian consumption), participants received an opportunity to try a mealworm truffle.

Each truffle consisted of a cluster made with ∼20 mealworms covered in dark chocolate. The truffles were always presented on a small ceramic plate and participants received a glass on non-carbonated water alongside their food sample. The consumption opportunity was accompanied by a questionnaire in which we first assessed quality expectations by following item: "On the basis of the information available, what quality do you expect from this truffle?". Participants rated this item on a 7-point scale ranging from 1 = *very bad* to 7 = *very good*. In the second question, participant indicated their willingness to consume the chocolate by either ticking off *yes, I am ready* or *No, I am not ready* and were instructed to follow their choice, serving as our central dependent variable. After voluntary consumption, we assessed participants' general subjective taste ratings (1 = *worst possible truffle* to 11 = *best possible truffle*) and they were asked for a price that they were willing to pay for a 100 g package of the product in the supermarket. Finally, participants completed a 27-item questionnaire assessing disgust sensitivity (35). Thereof, 14 items were rated on a 5-point scale ranging from 0 = *Strongly disagree (very untrue about me)* to 4 = *Strongly agree (very true about me)* and an example item is "If I see someone vomit, it makes me sick to my stomach.". The remaining 13 items, such as "You see maggots on a piece of meat in an outdoor garbage pail," were answered on a 5-point scale ranging from 0 = *Not disgusting* at all to 4 = *Extremely disgusting*. Also consumption habits (e.g., "In which supermarket do you prefer to shop?") as well as demographic variables were assessed. While participants completed the post-experimental questionnaire, the lab assistant prepared the payoff for the participant, paid him or her and dismissed the participant from the study, while also ensuring that the eating decision has been properly noticed (e.g., no difference occurred between an intention to eat the truffle and actual consumption behavior).

RESULTS

Preliminary Analysis Note

Because our research assistants directly approached prospective participants on campus, we sometimes recruited small groups of people. To avoid any effects of social influence, each participant sat at an individual table. Nevertheless, we analyse all our data with clustered standard errors at the session level to control for potential non-independence of observations. Not using clustered standard errors shows largely identical effects and does not alter the interpretation of the results. All analyses were performed using the software SPSS.

Effects on Willingness-to-Eat

First, we analyse the conditional probability of participants' willingness to consume the mealworm-truffle by Utilitarian vs. hedonic advertisement. The difference in the willingness-to-eat is statistically significant ($P = 0.035$, obtained from probit regression using clustered standard errors at the session level) and relevant in terms of effect size (76.2% for hedonic reasons; 61.3% for health and environmental claims combined, health claims alone: 56.6%, environmental claims alone: 65.6%). **Figure 2** depicts the result.

Turning to process-evidence, we evaluated how quality expectations mediate the effect of Utilitarian claims on actual consumption using a series of probit and ordinary least squares (OLS) regressions and the bootstrapping procedure recommended by Preacher and Hayes (36). **Figure 3** displays all regression results: First, there is a significant negative relationship between Utilitarian claims on willingness to eat ($p < 0.05$). Second, expectations significantly and positively predict the willingness-to-eat ($p < 0.001$, obtained from probit regression using clustered standard errors at the session level). Third, Utilitarian claims significantly negatively impact product expectations ($p = 0.013$, obtained from linear regression using clustered standard errors at the session level). Finally, in a model that includes both, the experimental condition as well as the expectations, the Utilitarian claims no longer predict the willingness-to-eat ($p = 0.14$), but the expectations do so highly significantly ($p < 0.001$, all values obtained from probit regression using clustered standard errors at the session level). To test for this indirect effect directly, we then employed a bootstrapping method. However, to the best of our knowledge,

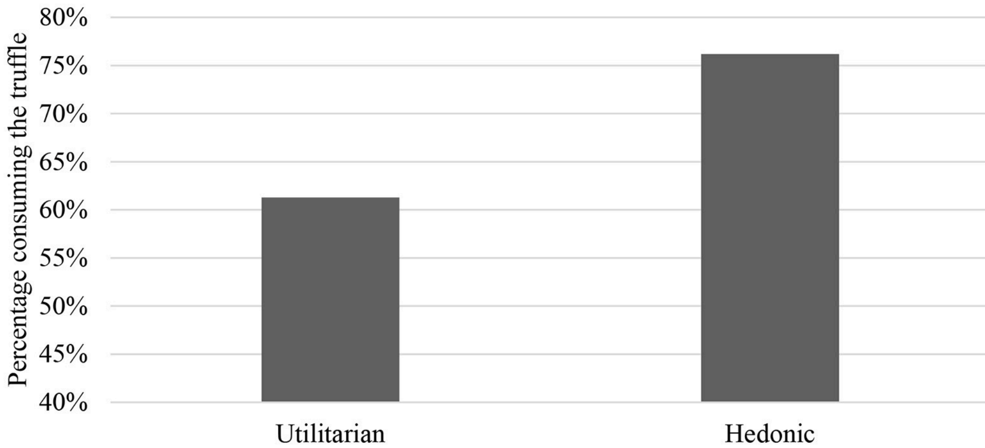

FIGURE 2 | Main results. Percentages of consuming the mealworm truffle (hedonic vs. Utilitarian claims).

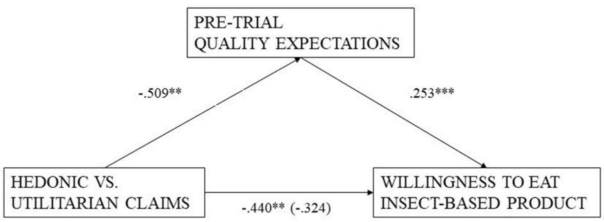

FIGURE 3 | Mediation results. Unstandardized regression coefficients for the relationship between advertising content and willingness to eat an insect-base product as mediated by pre-trial quality expectations. The coefficient between advertising content and willingness to eat insect-based product, controlling for pre-trial quality expectations, is in parantheses, ***$p < 0.01$, **$p < 0.05$.

this software does not allow calculation of clustered standard errors. Nevertheless, this mediation using 5,000 re-samples shows a significant indirect effect of Utilitarian claims on the willingness-to-eat via pre-trial quality expectations (effect: −0.2343, boot SE = 0.1198, 95% accelerated and corrected confidence interval = [−0.53; −0.06]).

As an initial summary, the results support the hypothesis that Utilitarian campaigns are less effective to their hedonic counterparts and that pre-trial expectations mediate this relationship. The results, therefore, are consistent with the moral and cognitive psychological research and refute the state-of-the-art approach in current insect marketing. As was shown for many products before, expectations provide a crucial mediator explaining why information content becomes behaviorally relevant.

Additional Analyses: Effects on Subjective Taste Ratings and Self-Reported Willingness-to-Pay

Next, we analyzed whether subjective taste ratings were also affected by the differentiated campaign focusing on either Utilitarian claims or hedonic claims. Because taste ratings can only be administered when a participant decided to actually try the truffle, this analysis is based on a reduced sample of those actually consuming the product. We observed a marginally significant effect indicating that Utilitarian claims are negatively related to participants subjective taste ratings (coefficient: −0.7428, $P = 0.07$, obtained from linear regression using clustered standard errors at the session level). As was the case for the willingness-to-eat, this effect rendered insignificant once including pre-trial expectations as a mediator. A direct assessment of the indirect effect using bootstrapping methodology corroborates this finding at the marginal significance level (effect: −0.1959, boot SE = 0.1622, 90% accelerated and corrected confidence interval = [−0.56; −0.02]). Turning to self-reported, not incentivized assessments of willingness-to-pay, we do not identify any significant effects of the experimental manipulation.

GENERAL DISCUSSION

The present research addresses the efficacy of the state-of-the-art approach to insect marketing, namely to highlight associate environmental or health benefits. The central result is that a shift to "hedonic" campaigns may be better suited to boost insect consumption. Participants were more likely to consume a mealworm truffle when this was advertised in a hedonic way. This finding is in line with results in the promotion of vegetables (37) where hedonic claims outperformed health-related information. Importantly and consistently with other research on consumer products [e.g., (33, 34)], we found that this effect is mediated by pre-trial expectations created when consumers initially engage with the advertisement. The same tendency was also found for taste effects. When insect truffles were marketed as "hedonic," experimental participants tended to like them better, following higher expectations.

These results challenge the effectiveness of existing campaigns that aim to promote insect consumption by highlighting its environmental and health benefits. Rather, our findings suggest that interventions emphasizing the delicious and unique culinary experience lead to a higher increase in insect consumption. However, further research is needed to confirm whether hedonic interventions are equally effective in non-laboratory settings (e.g., in restaurants, grocery stores, on the product packaging). It is plausible that potential consumers are generally reluctant to buy insect products on a regular basis due to their high price, which is comparable to beef. The reason for this lies in the high need for manual labor for producing edible insect protein up to now, but it is possible that increased demand will drive the development of rearing, harvest, and post-harvesting processing technologies, which in turn will reduce production costs.

Naturally, our results are limited due to several factors. First, we relied on a single market. Although we deliberately opted for a broad sample rather than a typical sample of undergraduate students, our results are essentially mute on the validity in other, unrelated markets. Importantly, effects may not necessarily be transferable to other cultures, countries, or even regions within one country. Furthermore, another limitation comes from the use of merely one product. Although this criticism applies to most of consumer research, it is important to state. However, in related research in which we use several products (13), we find high correlations of eating behavior across products. Put differently, it seems critical to motivate insect consumption in general, but once a person is willing to eat mealworm truffles, s/he is also prone to try mealworm burgers or other products.

Second, our research relied on advertisement campaigns that give very limited information. It could well be that deep information campaigns that—for example—transmit detailed environmental or health information, are better suited to convince prospective consumers about the attractiveness of insects as food. However, this seems rather unrealistic in terms of actual marketing campaigns. Typically, consumers attention (e.g., in stores, in TV, online) is rather limited and it is unlikely that they will engage in intensive information searches. Rather, insect companies will most likely use quick information campaigns (e.g., labels, coloring of packaging) to signal the healthiness or environmental friendliness of their product. In this sense, the current example was highly accurate.

As a summary, our results show that hedonic claims of insect-based products lead to higher expectations, which then result in higher consumption probability and higher taste ratings. Based on these findings, we propose using hedonic instead of utilitarian messages when advertising insect-based foods.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the local committee at Fresenius University of Applied Science (Cologne Campus) and did not require additional approval. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

SB, CB, and FC designed the research. CB and CS performed the research. SB, CB, FC, and AW analyzed the data. SB and AW drafted the manuscript. CB, FC, and CS gave feedback.

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Healthy Food as a New Technology—The Implications of Technological Diffusion and Food Price for Changes in Eating Habits

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Diet influences health and poor diets drive up healthcare costs for individuals and society as a whole. Multiple governmental programs in the US have aimed to educate citizens about diet choices, resulting in documented successes, as well as, unintended consequences such as increased food waste. Here we examine some of the relationships between healthy diets, food prices, and wealth by drawing parallels between the diffusion of technological innovation and healthy food diets. We introduce a simple modeling framework to estimate the adoption rates of healthy diets based on income and food prices, and describe the implications of the modeling results for the food industry and for government.

Keywords: diffusion, obesity, health costs, logistic growth, policy

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INTRODUCTION

In recent decades, obesity rates in the US have increased substantially[1]. Obesity has multiple negative health effects, including type II diabetes, hypertension, cardiovascular disease, and some cancers[2]. In 2012, Cawley and Meyerhoefer (1) estimated the health issues arising for obese persons increase medical costs by $2.7 k per year compared to a non-obese person. Over the entire US population, this leads to an estimated 6–10% of US health expenditures spent on diseases influenced by obesity (2). According to the US Centers for Disease Control and Prevention (CDC), adult obesity rates continue to climb: 39.8% of adults were considered obese in 2015–2016[3]. The term "obesity epidemic" has been used to describe the prevalence of obesity and its negative influence on human health.

A variety of factors are thought to drive the obesity epidemic, including increased caloric intake, reduced physical exercise, women entering the workforce at increasing rates (reducing the time spent preparing healthy meals at home), and consumer preference for convenient—and not necessarily healthy—meal options (2–5). Bleich et al. (2) studied eating habits in developed countries and discovered higher caloric intake is the driving force behind the obesity epidemic.

[1]"Prevalence of Overweight, Obesity, and Extreme Obesity Among Adults Aged 20 and Over: United States, 1960–1962 Through 2013–2014." Accessed July 25, 2018. https://www.cdc.gov/nchs/data/hestat/obesity_adult_13_14/obesity_adult_13_14.htm
[2]"The Health Effects of Overweight and Obesity|Healthy Weight|CDC," August 29, 2017. https://www.cdc.gov/healthyweight/effects/index.html
[3]"Adult Obesity Facts|Overweight & Obesity|CDC," June 12, 2018. https://www.cdc.gov/obesity/data/adult.html

While obesity is prevalent across all income levels in the US, low-income citizens are more likely to be obese than high-income citizens (6). The increased cost of healthy foods may also contribute to unhealthy eating habits.

Americans appear to be increasingly aware of the importance of a healthy, well-balanced diet[4]. Public schools in the US teach content developed by the United States Department of Agriculture (USDA), based on the USDA dietary guidelines, which specify recommended types and quantities of food to eat, and which are reviewed and updated every 5 years[5]. However, education does not always result in changes in behavior, and large parts of the US population continue to have unhealthy eating habits as defined by the USDA guidelines. Multiple factors beyond education influence eating habits, and in this work, we focus on food consumption patterns—specifically on healthy eating habits and the relationships between diet, food prices, and wealth.

GOVERNMENT PROGRAMS TO MEASURE AND ENCOURAGE HEALTHY EATING

The prevalence and cost of obesity has led the US government to take steps to address the epidemic. This includes understanding how Americans eat[6], promulgating legislation to encourage better food choices[7], requiring schools to offering healthier foods for breakfast and lunches[8], and providing nutrition education (7). These measures have had mixed results. The following paragraphs describe what has been done, as well as, research done after implementation to realize their effectiveness.

Quantifying the "healthiness" of a diet can provide insight on the causes of obesity. When the USDA releases their dietary guidelines, the organization tracks Americans' eating habits to monitor how well they are eating based on these recommendations. This comparison produces a number called the Healthy Eating Index (HEI). The USDA is using the HEI to monitor eating habits, and while many Americans are not meeting the required diet, the overall trend since the turn of the century is one of increasing HEI[4]. Although HEI scores increased from 49.1 to 59.0% from 1999 to 2012, only a small majority of Americans are eating as recommended, and this has major impacts on public health and healthcare costs.

In 2012, the USDA took a national household food acquisition and purchase survey to try to understand the characteristics of people at most risk for obesity[6]. Among other results, the study found that SNAP (Supplemental Nutrition Assistance Program, formerly the Food Stamps program) participants had a lower nutritional quality of household food acquisitions, as well has limited household access to healthy food retailers (8). Other studies also show that lower income Americans generally have a poorer-quality diet compared to their wealthier peers. Gu and Tucker (9) looked at the dietary quality trends of children and adolescents from 1999 to 2012, and while the HEI-2010 scores have improved over this time period, participants in the SNAP, National School Lunch Program, and School Breakfast Program have lower dietary quality than non-participants.

Many participators in SNAP do not choose healthy options when buying their own food (10). The 2008 Food and Nutrition Act defines eligible food items which can be purchased with SNAP dollars as any food or food product for home consumption. It does not differentiate between healthy and unhealthy foods, allowing participants to use buy junk food just as easily as healthier options. Perhaps giving SNAP participants incentives to buy healthy food, such as allowing for a percentage increase in benefits when choosing a healthy item or a percentage decrease in benefits when choosing an unhealthy item would encourage participants to change their eating habits (10).

The government is also encouraging Americans to make better dietary choices when going out to eat by showcasing nutrition information. Federal legislation that went into effect in May 2018 requires restaurants and similar food retail establishments that are part of a chain with 20 or more locations to disclose the calories of standard items on their menus. These businesses must also provide other nutritional information such as total fat, saturated and trans fats, cholesterol, etc. upon request[6]. Breck et al. did a study in 2013 to understand the effectiveness of calorie counts on menus, and found that higher-income patrons used the information to make food choices more than patrons with lower incomes (11).

To improve the nutrition of low-income American children, the Healthy Hunger-Free Kids Act was issued in 2010. It worked to change the nutrition standards of food served in schools. In 2012, requirements for this law were put into effect, requiring schools to increase fruit and vegetable offerings, reduce sodium in meals, require the use of whole wheat flour, and offer only non-fat milk, among other stipulations, in an effort to increase the healthfulness of food being eaten by American children[7]. These laws had variable success across the country. In a 2013 study of 10 school districts in California, students were found to be responding positively to the new meals[9]. Parents in the area overwhelmingly supported the new nutrition standards and were pleased their children would be eating better in school[7]. In another study, however, Amin et al. (12) researched fruit and vegetable consumption before and after the implementation of the new standards. Before the law went into effect, students were not required to take fruits and vegetables and consumed more of these items (0.51 cups before the requirement compared to 0.45 cups after). The study showed waste of fruits and vegetables

[4]Schap, TusaRebecca E. "The Healthy Eating Index: How Is America Doing? |USDA," 2016. https://www.usda.gov/media/blog/2016/03/16/healthy-eating-index-how-america-doing

[5]"Highlights, Nutrition Education in Public Elementary and Secondary Schools." Accessed July 25, 2018. https://nces.ed.gov/surveys/frss/publications/96852/

[6]"USDA ERS - FoodAPS National Household Food Acquisition and Purchase Survey." Accessed July 25, 2018. https://www.ers.usda.gov/data-products/foodaps-national-household-food-acquisition-and-purchase-survey/

[7]"Labeling & Nutrition - Calorie Labeling on Restaurant Menus and Vending Machines: What You Need To Know." WebContent. Accessed July 17, 2018. https://www.fda.gov/food/labelingnutrition/ucm436722.htm

[8]"Nutrition Standards for School Meals | Food and Nutrition Service." Accessed July 17, 2018. https://www.fns.usda.gov/school-meals/nutrition-standards-school-meals

[9]"Atkins Center Study: Students Prefer New, Healthier School Meals." UC Berkeley School of Public Health, October 16, 2013. http://sph.berkeley.edu/atkins-center-study-students-prefer-new-healthier-school-meals

increasing significantly as well—students discarded 0.39 cups of fruits and vegetables after the standards were implemented, compared to 0.25 cup prior to the new law, a 56% increase. Due to the negative reaction to the 2012 standards, the USDA amended the menu planning laws, allowing flexibility to the requirements for whole grain, low sodium items, and non-fat unflavored milk.

Investigators have attempted to understand the scope and effectiveness of governmental programs. McGeary (7) showed that state and federal funding increased from $0.66 million in just seven states in 1992, to $247 million in all 50 states plus the District of Columbia and Puerto Rico in 2006. The results of the study showed that money spent on nutritional education was successfully reducing the prevalence of obesity and overweight adults in the United States. However, the impacts were greater for higher educated and higher income adults, suggesting education programs have less impact on lower income, less educated individuals. Similarly, Frederick et al. (13) reported reduced rates of obesity for adolescents, but with impacts divided according to the teenagers' socioeconomic status: higher income adolescents' obesity rates decreased, while lower income adolescents' obesity rates increased slightly.

NON-GOVERNMENTAL APPROACHES TO MEASURING DIET QUALITY

Another organization focused on eating habits is the American Heart Association (AHA). They have released recommendations for a diet to help reduce cardiovascular disease in America[10]. The AHA diet has a high intake of fruits, vegetables, whole grains, nuts, and fish and tries to minimize sugar, salt, processed meat, and saturated fat. Rehm et al. (14) used data from the National Healthy and Nutrition Examination Survey between 1999 and 2012 to create a point rating system for how healthy a diet is based on the ideal AHA diet. The maximum number of points is 50; poor diets are classified as those meeting <40% (or 20 points) of the diet's goals, while intermediate diets meet 40–80% (or 20–40 points) of the goals. Those meeting the ideal diet of >80% adherence were not included in this analysis. **Figure 1** illustrates the stratification of diet quality by income level. **Figure 1**, based upon (14), depicts that although Americans have improved their diets over the past decade and a half, high-income citizens are improving their diets more rapidly than are those with lower income.

The dotted line represents the watershed between poor to intermediate diet quality in the AHA system. The data shows people of all incomes eating a better diet over time, with higher income people starting at a higher diet quality and increasing diet quality faster than the other brackets.

DIET CHOICES AND FOOD PRICES

As detailed above, multiple investigations have demonstrated that educational programs seem to have a disproportionate effectiveness for higher income citizens. Understanding how Americans' choose their diet could lead to insight on ways to increase the healthfulness of their diet, especially for low-income citizens. A 2016 study by Beheshti et al. (15) created simulation models which looked at food choices and analyzed these options based on three ways to choosing food; energy cost (price per calorie), unit price (price per gram), and serving price (price per serving). They found dietary food choices for low-income people to be based primarily on price per calorie.

Overlaying this finding—i.e., the importance of price per calorie—with changes in food prices, can provide additional insight into the challenges facing the wider spread adoption of healthy diets. Christian and Rashad (16) looked at changes in the price of food from 1950 to 2007 and found that fruit and vegetable prices increased over time, while the price of snack foods decreased. They were then able to correlate this easier access to calorie dense food to increased obesity rates over time. Fruits and vegetables generally have lower energy densities (lower calories per weight) than foods with refined grains, added sugars

[10]"The American Heart Association's Diet and Lifestyle Recommendations." sitecoreprod.heart.org|beta.heart.org|www.heart.org|heart.org|*.azurewebsites.net|localhost. Accessed August 6, 2018. https://www.heart.org/en/healthy-living/healthy-eating/eat-smart/nutrition-basics/aha-diet-and-lifestyle-recommendations

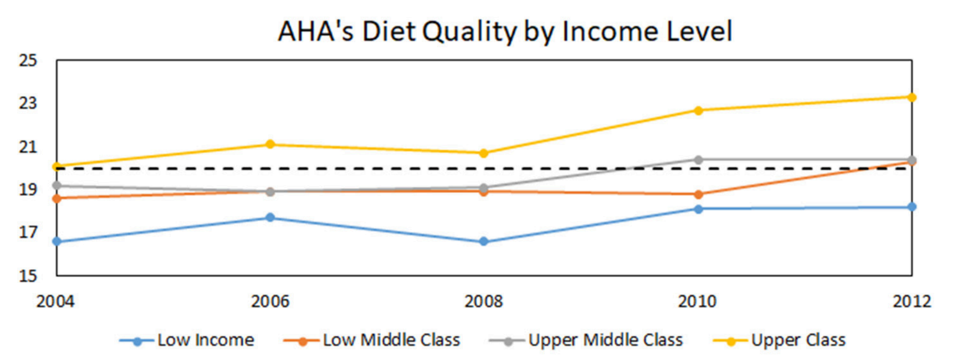

FIGURE 1 | Time course of income-stratified population scores on AHA diets scores. Dotted line represents threshold between poor and intermediate. Adapted from data in Rehm et al. (14).

and fats. For people with limited incomes, healthier food is difficult to justify.

We wondered if healthy food prices alone are the critical variable of interest. We decided to explore the *ratio* of certain healthy and unhealthy foods. When we did so, we found that the price ratios of healthy to unhealthy foods was actually decreasing over time. Using historical data (17) of the cost of a banana (an exemplar healthy snack food) and the cost of a representative chocolate candy bar (an exemplar unhealthy snack food) starting in 1980 and ending in 2012 to create a ratio of price for banana to chocolate candy bar creates **Figure 2**:

Figure 2 shows that in 1980, the cost of a banana was 1.3x the cost of a chocolate candy bar, and in 2012, bananas were only 0.6x the cost of a chocolate candy bar. The best fit linear line shows a 2.3% decrease in the cost ratio of bananas to chocolate candy bars from 1980 to 2012. Even with the limited scope of the data above, knowing that lower income Americans chose food based on price per calorie, the trend of being able to replace a chocolate candy bar with a banana at a similar price could help explain the increase in the HEI over the past few years. The option to adopt a healthier diet is becoming more accessible—the question is how to convince Americans to change the way they eat?

HEALTHY FOOD AS A “TECHNOLOGICAL INNOVATION”

One explanation for the increase in diet quality could be linked to the knowledge of the effects of obesity. The spread of this awareness could be compared to what Rogers [(18), p. 6] calls the “diffusion of innovations.” In his book of the same name, he states “Diffusion is a kind of social change, defined as the process by which alteration occurs in the structure and function of a social system.” This term can be used both for technology and an idea or practice. Rogers uses an s-shaped curve to show how innovations are adopted in a community. Initially only a few people adopt the new technology. Then as the idea is vetted by the early adopters, use of the new innovation spreads rapidly until it is widely accepted. Finally, adoption slows as it reaches a saturation point, or when the whole population uses the new technology. Examples of diffusion include farming practices, clothing fashions, and internet adoption.

Depending on the innovation, the rate of adoption can vary. Innovations which have a direct and visible advantage are more likely to be accepted faster than those with not so visible or easily understood advantages. Eating well could be considered a preventative innovation, which Rogers describes as an idea that is adopted now to lower the probability of some unwanted event later. These innovations are slow to catch on because the advantages occur in the future, or in this case, may not happen at all; depending on factors such as heredity, thyroid problems, and fitness routines, people can still suffer from diseases associated with obesity even with a healthy diet. An example Rogers uses in his book for a preventative innovation and its rate of adoption is seatbelt use [(18), p. 233]. In 2002, only 73% of Americans used their seatbelts, and 60% of auto deaths were by those not wearing them. When the non-users were asked why they did not use a seatbelt, even if aware of the high risk in the case of an accident, the general consensus was that the cost and effort required to use a seatbelt is greater than the possible benefits. Non-users also felt that the probability of being in an accident was negligible. There are clear parallels between healthy eating and seatbelt use—e.g.,

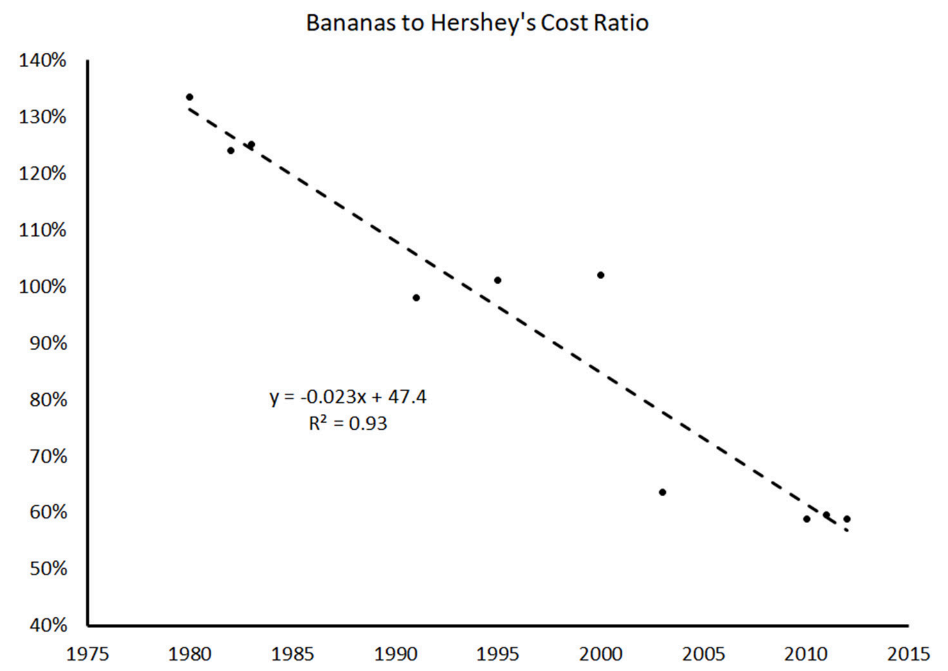

FIGURE 2 | Ratio of exemplar healthy snack cost to that of exemplar unhealthy snack cost, illustrating steady decrease in the relative cost of the two.

persons who have high risk thresholds might not use seatbelts, nor worry about the health of their diet. On the other hand, food has dimensions that reach far beyond calories and health—there are significant socio-cultural aspects to food consumption that make it a more complex realm than the use of safety belts. This is an inherent limitation to our use of this parallel.

In Martin and Robinson (19) used income to predict internet usage in American households. Having access to the internet has been compared to discovery of the alphabet; users who remain without internet face increasing economic, social, health, and other disadvantages. The study aimed to analyze inequality in internet use from 1997 to 2003 by comparing internet adoption to income levels and then predict when these levels would have access to the internet. This study was particularly interesting as income is the variable which most directly correlates with barriers to internet use- the technology had to be seen as useful, as well as, affordable. Their "optimistic" model had everyone eventually getting the internet, but with a dichotomous variable for income-meaning that all groups had the same rate of adoption, but higher income people had a head start on the technology. This follows typical early adopter behavior, and separating adopters based on income instead of lumping everyone together allows for a visual representation of adoption based on economic class. **Figure 3A** shows both populations reaching 100% internet usage, with economically disadvantaged people reaching full adoption later than advantaged people (poor vs. rich, respectively in this case). In contrast, when the authors assumed that disadvantaged people are unlikely to reach the same final level of adoption, the curve as shown in **Figure 3B** results.

In the case of healthy eating, graph 3b, which depicts not everyone reaching the same level of eating well, is more likely, especially because it is a preventative innovation.

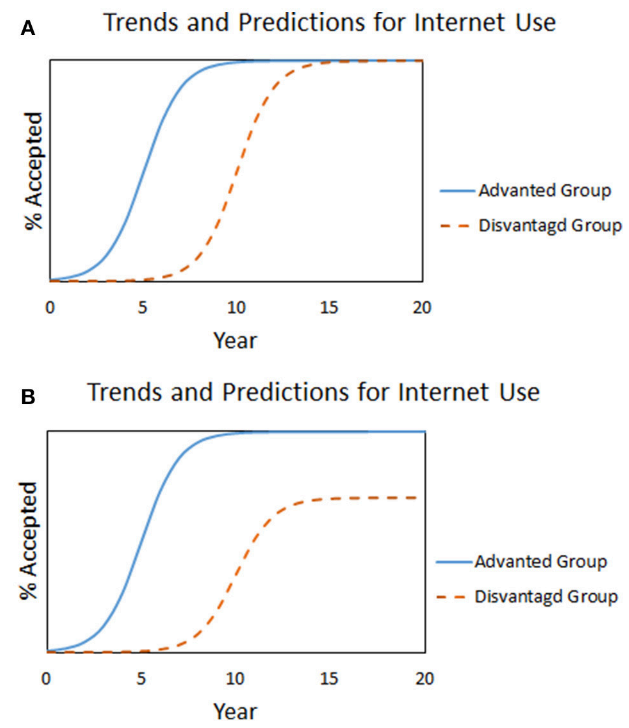

FIGURE 3 | (A,B) Internet adoption over time for two wealth-delineated populations, under an assumption of 100% final adoption for both groups **(A)**, and unequal final adoption rates **(B)**. Adapted from Martin and Robinson (19).

MODELING DIET CHOICE UNDER ASSUMPTIONS OF CHANGING FOOD PRICES

To do a predictive analysis of eating habits by income using a similar approach as above, we used AHA healthy diet data [from (14)], analyzed as population percentages eating poor, intermediate, or good diets. The researchers found that the vast majority (>95%) of the population was in either the poor diet or intermediate diet category. This makes it possible to simply report the results as percent of population eating the healthier (intermediate) diet verses the poor diet. These results, split between low- and high-income groups (and ignoring the middle-income groups), for a 9-year period, are summarized in the following table:

Two patterns emerge in the table above. The first is that both populations (high- and low-income) are eating better over time—a promising finding, which has been seen in other research. Second, as might be expected if healthy foods command a higher price, thereby making it less accessible to less-wealthy persons, the adoption rates of healthy diets are lower among the low-income population.

To model the adoption rates of an intermediate diet, we used a modification of the Verhulst incarnation of a logistic growth model (20). The unmodified logistic model is as follows:

$$\frac{dP_i}{dt} = r_i P_i (1 - \frac{P_i}{K_i}) \quad (1)$$

Where P_i is the fraction of population i adopting a healthy diet (dimensionless), r_i is the intrinsic adoption rate for population i (dimensions of inverse time), and K_i is the steady-state maximum fraction of population i expected to achieve the intermediate diet (dimensionless).

Our modification to Verhulst's approach involved including the impact of food price on adoption rate by making the variable r_i a function of food price, specifically by making it inversely proportional to food price, per the following equation:

$$r_i = \frac{b_i}{d} \quad (2)$$

Where b_i is the price insensitivity—different for each income group because people with more disposable income have higher price insensitivity, as they are more likely to adopt healthy foods that cost more—and d is the cost of the technology. The variable d is not subscripted, as the cost is assumed constant across wealth groups. Discretizing the equation ($\Delta t = 1$ year), the following equation is used to estimate the growth rate of adoption for healthy foods:

$$P_{i,\,n} = P_{i,\,n-1} + \frac{b_i^* P_{i,n-1}}{d} * (1 - \frac{P_{i,n-1}}{K_i}) \tag{3}$$

We used 2017 seat belt adoption rates, which were separated by income bracket, to set the K_i values as 90.1% for high-income and 86.7 for low-income populations[11] Seat belts are a preventative innovation that have been universally available in US passenger vehicles for half a century, and required by law for much of that time. Seat belts are virtually zero-cost because of their ubiquity (and perhaps arguable negative cost due to the fines associated with not wearing them).

Utilizing the starting values from **Table 1** to populate $P_{i,\ 2003/4}$. We set d to an initial value of 1.0 (arbitrarily, as it is the b/d lumped parameter that drives the model results), and set it to decrease by 2.3%/year based on the analysis of banana vs. chocolate candy bar cost vs. time from above. We then instantiated equation 3 in Excel for a time step of 2 years and varied the values of $b_{Low-Income}$ and $b_{High-Income}$ such that the 2011/2012 values of Pi were in agreement with the tabulated data. Doing this yielded a b-value for high-income group of 2.0, compared to 0.95 for the low-income group, implying high-income citizens are more likely, by approximately a factor of two, to pay for healthy food than are low-income citizens.

Although these modeling results must be interpreted with caution, they do allow rough forecasting of the rate at which healthier diets will be adopted by various income groups, as shown in **Figure 4** below.

Figure 4 suggests that under a 2.3% annual decrease in the relative price of healthy vs. less-healthy food, nearly 90% of high-income persons will have adopted an intermediate diet in four decades time, while slightly over 70% of low-income persons will have done so. These results are sensitive to the rate of annual decrease of the relative prices of food. If instead of 2.3%, a 3.0% annual decrease is assumed, high-income citizen adoption is roughly the same while low-income citizens achieve 80% adoption in four decades. Conversely, if the rate is only 1.5%, high-income citizens achieve 78% adoption, while low-income achieve only 66% adoption. These results suggest that driving down the cost of healthy foods—both raw and processed—could be a critical approach to improving diets.

This model also only goes through 2012. This is because the data on how Americans are eating based on income has only been analyzed and compiled up to this date. While there likely have been many changes to food prices and eating habits since 2012, the data to extend past this date is not available. It would be interesting to see if current data fits the model above.

[11]"Explore Seat Belt Use in the United States|2017 Annual Report." America's Health Rankings. Accessed July 23, 2018. https://www.americashealthrankings.org/explore/annual/measure/seatbelt_use/state/ALL

AMERICANS MAY BE OPTING FOR HEALTHIER PROCESSED FOODS—CURRENT FOOD TRENDS

With higher-income Americans eating healthier and demanding a greater selection of healthy products, their purchasing habits at grocery stores and restaurants is changing as well. Kraft, Heinz, Campbell Soup, and J.M. Smucker reported weak sales trends at the end of 2017, and noted that Americans are avoiding once-popular processed food (boxed and canned) in favor of fresher, higher-quality items[12].

Traditionally, big food manufacturers and fast food restaurants have provided highly accessible unhealthy foods—a trend driven by the desire for profit and the popularity and hence high sales of unhealthy food[13]. Companies are replacing the ingredients in their products with healthier options, and large corporations are purchasing smaller health-food companies in an attempt to leverage the small-company brand and know-how. McDonald's provides a case study: as their sales declined, the company started switching many of their ingredients to healthier alternatives, including 100% real beef, chickens that are not fed human hormones, and using butter instead of margarine[14,15]. Another major food player, General Mills Inc. (GMI), started investing in healthier options, most notably with the purchase of Annie's Homegrown in 2014[16]. After this acquisition, GMI became the third largest producer of natural and organic products, with this portfolio predicted to reach $1.5 billion in net sales by 2020[17].

Grocery stores are also impacted by the changes in consumer preference, and are using their large-volume purchasing power to force suppliers to change their offerings. For example, grocery giant Walmart partnered with an organic products company in 2014, resulting in the offering of many products costing ∼25% less than traditional organic products[18]. Though the line was discontinued just 2 years later, Walmart continues to offer organic produce, as well as, their Great Value brand

[12]"Big Food Faces Pressure as Consumers Seek Fresh Meals, Snacks - WSJ." Accessed July 17, 2018. https://www.wsj.com/articles/food-makers-still-searching-for-stronger-u-s-sales-1518791481

[13]"Food for Thought." The Economist, December 15, 2012. https://www.economist.com/special-report/2012/12/15/food-for-thought

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TABLE 1 | Rates of adoption of intermediate healthy diets by two income-based populations, as reported by Rehm et al. (14).

	2003–2004 (%)	2005–2006 (%)	2007–2008 (%)	2009–2010 (%)	2011–2012 (%)
$P_{Low-Income}$	31.9	37.4	31.0	39.3	38.4
$P_{High-Income}$	48.5	51.8	51.1	57.9	62.5

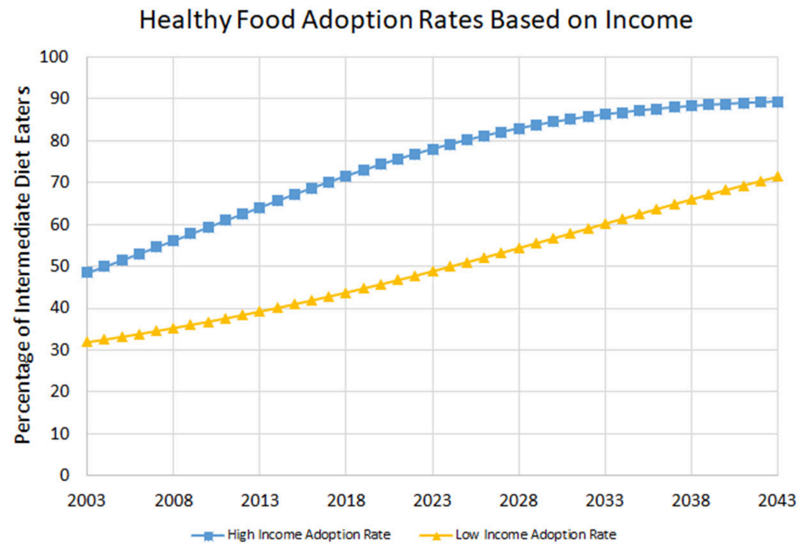

FIGURE 4 | Projected adoption of intermediate health diets by two income groups, based on parameters estimated as described in text.

processed foods with organic content[19]. Discount retailer Aldi is also entering the healthy food market by offering organic fruits and vegetables, removing artificial growth hormones from their dairy products, and removing synthetic colors, partially hydrogenated oils, and added MSG from all its private label products, among other health initiatives[20]. Aldi has already disrupted the grocery store market in the UK and is currently investing 3 billion into expanding its US market[21].

This effort to appeal to high-income Americans is leading to healthier food for lower income Americans as well. Many companies use a platform system in which products are the same regardless of where they are purchased, for example, McDonald's was founded in 1955 with the belief that their food should taste the same in Alaska as it does in Alabama[22]. As larger companies attempt to keep market shares of wealthier consumers (i.e., consumers that have both the desire and means to purchase healthier foods) by altering their products, their use of platform systems implies that all of those new products will be available to lower income consumers as well. In GMI's case, the purchase of Annie's Homegrown has resulted both in a large expansion of available products, and greatly increased availability of those products, which are now distributed widely across the country[23].

CONCLUSION

The obesity epidemic is a complex issue with multiple drivers. But it is not insurmountable, as shown by the success of educational efforts, and by the progression of healthy eating index scores over time. It is important to recognize though that for healthy diet choices to be made by all citizens—not just those with disproportionately high access to resources—factor such as convenience and cost must be addressed. A hopeful trend is the increasing popularity and availability of healthy foods. This trend, when combined with continued educational efforts, has great potential to help larger fractions of the population lead healthier lives.

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AUTHOR CONTRIBUTIONS

AD and DR contributed conception and design of the study. AD collected and organized the articles, wrote the first draft of the manuscript and ran multiple scenarios of the model. DR conceived the approach of considering new-food as technological diffusion, and built the first iteration of the model. Both authors contributed to manuscript revision, read, and approved the submitted version.

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REVIEW
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The Next Generation of Sustainable Food Packaging to Preserve Our Environment in a Circular Economy Context

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Packaging is an essential element of response to address key challenges of sustainable food consumption on the international scene, which is clearly about minimizing the environmental footprint of packed food. An innovative sustainable packaging aims to address food waste and loss reduction by preserving food quality, as well as food safety issues by preventing food-borne diseases and food chemical contamination. Moreover, it must address the long-term crucial issue of environmentally persistent plastic waste accumulation as well as the saving of oil and food material resources. This paper reviews the major challenges that food packaging must tackle in the near future in order to enter the virtuous loop of circular bio-economy. Some solutions are proposed to address pressing international stakes in terms of food and plastic waste reduction and end-of-life issues of persistent materials. Among potential solutions, production of microbial biodegradable polymers from agro-food waste residues seems a promising route to create an innovative, more resilient, and productive waste-based food packaging economy by decoupling the food packaging industry from fossil feed stocks and permitting nutrients to return to the soil. To respond to the lack of tools and approach to properly design and adapt food packaging to food needs, mathematical simulation, based on modeling of mass transfer and reactions into food/packaging systems are promising tools. The next generation of such modeling and tools should help the food packaging sector to validate usage benefit of new packaging solutions and chose, in a fair and transparent way, the best packaging solution to contribute to the overall decrease of food losses and persistent plastic accumulation.

Keywords: food packaging, sustainability, biodegradable, bio-sourced, waste-based

INTRODUCTION

Around 100 million tons of foods are wasted annually in the EU, nearly 30% of the agri-food supply chain (1), which leads to huge environmental impacts (high carbon footprint and blue water footprint, vain land use, etc.) (2, 3). Food waste should rise to over 200 million tons by 2050 while an increase of 50% in food supplies will be needed globally (4, 5). Even if the relation between shelf-life and food waste is not straightforward, a large part of food wastage is related to the short shelf-life of a lot of fresh produce inherent to its biological origin. Moreover, inaccuracies in, or misunderstanding of, food date labels are estimated to cause over 20% of the avoidable disposal of still-edible food (6).

Recently, packaging was identified as an essential element to address the key challenge of sustainable food consumption and is gaining interest among scientists (7, 8). Packaging is a central element to food quality preservation by mainly, controlling gas and vapor exchanges with the external atmosphere, contributing to preserving food quality during storage, preventing food safety issues (prevention of food-borne diseases and food chemical contamination) and extending food shelf-life. Significant benefits are expected in terms of reduction of food waste thanks to shelf life extension (9, 10), especially by using a well dimensioned packaging material, adapted to food needs in term of preservation (8, 11). However, packaging is usually wrongly considered as an additional economic and environmental cost rather than an added value for waste reduction. Moreover, primary packaging[1] is, currently, not always well adapted to the food needs and therefore does not efficiently and sufficiently contribute to maintain the shelf life of the food (9, 10, 12).

When a food product is thrown away, the packaging is also discarded leading to an additional environmental burden. In our plastic based economy, packaging materials are principally oil-based. Plastic world production increased by 4.2% between 2015 and 2016 to reach 335 million tons. 23 million tons of plastic packaging are produced each year in Europe (92 million tons expected in 2050)[2]. After an exclusively single and very short use inherent as food packaging, 40% ends up in landfill corresponding to 9 million tons of plastic packaging waste that is fated to accumulate in soils. 32% leak out of collecting and sorting systems and finally end in the soil and ocean as well (13, 14). This marine and soil litter first degrades into micro- and then into nano-sized particles that could thus easily penetrate into living organisms such as fish and then be fed up the food chain, all the way to humans with dramatic deleterious long-term adverse effects (15). If production and use continue within the current linear framework, and if nothing is done by 2050 there may be more plastic than fish in the ocean, by weight (13).

To tackle issues related to oil-based packaging, a lot of attention has been paid to raw materials to replace non-renewable oil resources. However, currently marketed bio-sourced bio-plastic (such as Bio-PE, PLA, and more) use food resources such as corn or cane sugar. They contribute to increase food security concerns and pressure on agricultural land (16). Moreover, most of these bio-sourced bio-plastics are not biodegradable nor home-compostable (bio-PE, bio-PET) or are fit only for industrial composting (PLA) which contributes to complicating the waste management: separate collecting and sorting of these materials are thus needed (17, 18). The term "bio" itself appears confusing for consumers, referring on one hand to the nature of resources and on the other hand to material end-of-life (biodegradability). Finally, commercially available eco-efficient packaging solutions are facing difficulty in being considered convincing "sustainable packaging" because their economic and environmental "cost vs. benefit" balance is not obviously and simply demonstrated, or even controversial, for most stakeholders who request trust to be restored and existing green washing suspicion to be lifted.

In this context, it appears that food and packaging waste reduction means more rather than less packaging, or oil-based resources substitution by renewable resources. In addition to mitigating the negative burden of packaging resources and packaging waste management, a sustainable food packaging also increases its positive usage benefit, which is the reduction of food losses and waste. This is achieved by primarily fitting the food requirements to preserve food quality and safety on the whole supply chain and mainly at distribution and consumption stages. Considering the product and its packaging as a complete system is thus primordial to optimize the sustainability of food/packaging systems as a whole.

This paper aims to demonstrate how packaging could be a key element of sustainable food consumption by simultaneously decreasing food waste and losses and the burden on resources and packaging waste management. In a first part, the primary fundamental role of food packaging will be first recalled, then, in a second part, the major identified challenges to the commercialization of innovative sustainable solutions in the food packaging area will be highlighted, focusing on "full bio-packaging" solutions, which means issues from non-food renewable resources which are biodegradable in natural condition. A special focus will be paid in this part on the need of *early guidance tools* for packaging users and producers to efficiently choose the suitable packaging material and *fast track* innovations up to market penetration. Then, in a third part, some solutions to overcome those problems will be presented based on last inputs from state of the art that bring significant advances in the field of eco-innovative packaging solutions in terms of knowledge, technical up-scaling, user-driven approaches and decision-support tools to provide *new products and services*. This will be illustrated by using a thorough analysis of the scientific literature, paying attention also to the key elements of the European environmental and safety regulation on this topic. Lastly, in a fourth part, the expected impact by horizon 2050 of the aforementioned solutions will be summed up.

PRIMARY FUNDAMENTAL ROLE OF FOOD PACKAGING

The primary fundamental role of food packaging is to preserve food quality and safety, to reduce food waste and food-borne diseases, and to reduce the corresponding useless negative impact that producing and distributing uneaten or inedible food has on our environment and economy. That means that packaging functional properties must fit the food requirements, especially its mass transfer properties.

Mass transfers through the packaging material (transfer of gases, water vapor, aroma compounds, etc.) play a major role

[1]The retail or consumer pack that contains the sales unit (e.g., a plastic bag, glass jar, or steel can, or a plastic crate for loose fresh produce).

[2]PlasticsEurope, Plastics—the Facts 2013 (2013); PlasticsEurope, Plastics—the Facts 2015 (2015).

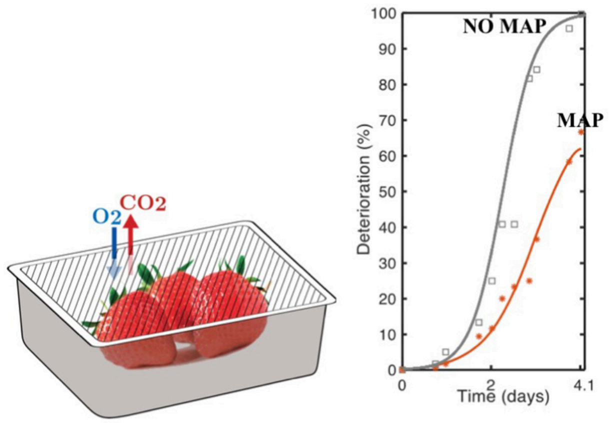

FIGURE 1 | Benefit of MAP (Modified Atmosphere Packaging) compare to a control with NO MAP to limit the degradation rate of strawberries "*Charlotte*" variety (graph on the right)-adapted from Matar et al. (10).

in the control of food degradation reactions by defining around the product an atmosphere whose composition is favorable to the slowing down of the reactions, thereby extending food shelf life. For instance, the control of O_2 concentration in headspace limits oxidation reactions and growth of aerobic microorganisms, two main causes of food deterioration during storage. This technology, called Modified Atmosphere Packaging (MAP), relies on the modification of the internal atmosphere by the product itself (passive MAP) or by gas flushing or use of gas emitters or scavengers (active MAP) (8, 19, 20). In both cases, the optimal atmosphere is achieved thanks to the mass transfer properties of the packaging material, especially its permeability toward gas and vapors, i.e. its ability to let migrants pass from the external atmosphere toward the internal one.

Permeability properties of the food packaging, also called barrier properties, rarely fully meet the food requirements. These barrier properties are either too low (case of O_2 sensitive food products for which high barrier materials are required) or too high. We can cite for example, the case of respiring products such as fresh fruits and vegetables, where the plastic film is perforated to compensate for the too high barrier properties of the packaging.

As a result, current packaging is usually over or poorly designed and not well adapted to the food needs. Packaging does not efficiently and sufficiently contribute to maintain food quality although much higher benefits in terms of reduction of food losses could be achieved using well dimensioned packaging material (**Figure 1**) (9, 10, 19).

Packaging is usually wrongly considered as an additional economic and environmental cost rather than an added value for food loss reduction by improving food shelf-life. In order to contribute to solving the environmental issues of the food/packaging system as a whole, it is necessary to consider, in addition to the environmental impact of the packaging material itself, its contribution to the reduction of environmental impact of food loss and waste (8, 12).

CURRENT CHALLENGES IN THE FIELD OF FOOD PACKAGING AND SUSTAINABILITY

In the very dynamic worldwide food packaging sector, marketed innovations essentially focus on practical and easy-to-use aspects as well as conviviality and aesthetics for consumer attractiveness. Some of the marketed innovations are claiming to be sustainable either by their resources (bio-based) or their end of life (biodegradable) but without a full and fair assessment of their overall environmental benefit. Most of these eco-friendly innovations are less eco-friendly than expected: for instance, materials vary significantly in terms of quantity of renewable resources used in their formulation and may or may not be readily compostable as is often claimed. None of these innovations claimed to be sustainable for its usage benefit, which is food loss reduction.

The crucial societal stake of sustainable food consumption still needs to be bridged with a wealthy R&D sector, proposing a large reservoir of innovative packaging technologies that will improve packed food sustainability.

In particular, a lot of research has been done on the development of **bio-packaging** solutions, i.e., either bio-based packaging materials made from renewable resources and/or biodegradable materials. However, packaging stakeholders are facing the difficulty of overcoming specific **technical issues** with these bio-packaging materials that currently hinder large market uptake. These technical issues are in particular, an avoidable raw material variability and a too narrow processing window, compared to common oil-based counterparts, that hinders their scaling up and diffusion among packaging producers. In addition, the **lack of tools** to help users to tailor packaging to food needs (e.g., to fit packaging mass transfer properties to food requirements) and to decipher the real sustainability of bio-packaging innovations and packaging at large, especially in terms of food losses reduction, prevents stakeholders to fully seize the economic, societal, and environmental opportunities of these innovations.

The Confusing Long Term Environmental Benefit of Eco-Friendly Packaging Solutions

Despite extremely dynamic research and development on bio-sourced and/or biodegradable materials (more than 1,400 scientific publications/year on the last 10 years–**Table 1**), commercially available bio-packaging does not yet properly meet the huge market and consumers demands.

Bio-packaging development is hampered by serious controversies about its technical, social, and environmental benefit (ambiguous claims on environmental impacts, competition between food and non-food usage of agricultural resources, high environmental cost of already existing "bio" solutions, troublesome compostability of PLA, green washing suspicion, and more) (17).

The "bio" label itself (bio-based, biodegradable, bioplastic…) is misunderstood by customers. While they might interpret the "biodegradable" labeling to mean "fit for home composting,"

TABLE 1 | Summary of Tensile Properties (Tensile Strength, Tensile Modulus, and Strain at Break) and oxygen permeability of some Biodegradable Polymer Matrices [adapted from (21)].

Polymer	Tensile strength (MPa)	Young's modulus (GPa)	Strain at break (%)	PO2 x 10^{17} (mol m^{-1} s^{-1} Pa^{-1})[a]
PCL	19 à 21	0.21 à 0.33	300 à 897	26
PBAT	>84	0.04	>200	–
PBSA (Bionolle)	20	0.44	20	–
PLA	21	0.35	3	41
P(HB-co-HV) with 3% HV	40	3.5	5	1–7
P(HB-co-HV) with 3% HV and 20% of milled wheat straw[b]	19.6	3.03	1.03	–
Polypropylene	34.5[c]	1.7[c]	400[c]	
Polyethylene -terephtalate	56[c]	2.2[c]	–	0.72[d]
LDPE	10[c]	0.2[c]	620[c]	95.7[e]

[a]*Measured at ambient temperature and 0% RH.*
[b]*From Berthet et al. (22).*
[c]*From Khanna and Srivastava (23).*
[d]*From Auras et al. (24).*
[e]*From (10).*

in reality, the large majority of current biodegradable plastics (e.g., PLA) can only biodegrade under very specific conditions of constantly high temperature and humidity in industrial composting installations, and they are neither fit for home composting nor do they decompose in reasonable time when littered, implying damaging consequences for fauna and flora (e.g., aquatic ones) (15).

Encouraged by a favorable European regulation [EU Circular Economy Package, EU Waste legislation (25), etc.], recent innovative research has focused on developing bio-plastics from organic waste streams (crop residues, agro-food by-products, sewage sludge, etc.) seeking to enter a circular economy concept that does not compete with food usage and that is fully biodegradable to respond to the overwhelming negative externalities of our plastic packaging: today, 32% of plastic leaks out of collection systems into the environment, of which 8 million tons leak into the ocean each year. The latter is equivalent to dumping the contents of one garbage truck into the ocean every minute, which is estimated to increase to the contents of four trucks per minute by 2050 if no action is taken (13).

There is a real need to develop convincing sustainable packaging materials decoupled from fossil feedstocks, with no competition with food resources and with a real advantage to solve the issue of the accumulation of persistent plastics in our environment. This could be achieved by enhancing the conversion of *agricultural and agro-food residues* into "*naturally biodegradable*" packaging[3] with a fair and transparent eco-efficiency performance assessment. It is also necessary to enlarge industrial process-ability and functionalities of these materials that must be tailored to usage requirements while optimizing their cost. The organic residues used as feedstocks for this bio-packaging production must be unavoidable and worthless by-products and residues of agricultural and agro-food industries that are thus turned into value-added raw materials for bioplastics production[4].

Need to Clearly Assess the Benefits of Packaging Solutions to Reduce Food Waste and Losses

Although there is plenty of evidence of the benefits of using innovative packaging solutions to extend food shelf-life, there is no general approach that permits to assess the shelf life of a packed product and especially the gain of shelf life that could be achieved by using well designed primary packaging, with functional properties that match the food requirements well. For instance, searching on the Easy Web of Science tool for the last 10 years, with the following keywords: Modified Atmosphere Packaging, and Shelf life separating those two keywords with the connector AND, 1,566 articles were found (done in May 2018) proving the dynamism of research in that field.

Among innovative packaging solutions, MAP and especially active MAP, where active compounds are, for instance, emitted from packaging toward headspace creating a modified atmosphere that limits microbial spoilage, is a good example of eco-packaging solutions (19, 27). However, these solutions remain difficult to adapt and up-scale because they need to be clearly fitted to the specific needs of the food. For instance, in the case of passive MAP when the product itself creates the modified atmosphere due to its aerobic metabolism (e.g., the case of respiring product), the O_2 and CO_2 permeability property of the film must be adapted to the respiration rate of the product

[3]**Naturally biodegradable**: fully biodegradable in natural land conditions or home composting conditions as opposed to industrially compostable materials such as PLA.

[4]**Agro-waste** is defined as plant or animal residues that are not (nor further processed into) food or feed, and create additional environmental and economic issues in the farming and primary processing sectors. These residues should not be mistaken with the avoidable agro-food waste. Unavoidable primary agricultural residues account for about 50% of the fresh weight of harvested crops and represent a potential of 90 MTOE, far ahead of other waste sources such as round wood production (57 MTOE), municipal and other waste (42 MTOE) and tertiary forest residues (32 MTOE) (26).

(11, 28). There is a high risk of failure if empirical trial-and-error approach is used to adjust the film permeability, the gaseous atmosphere composition or the quantity of active compound to obtain the expected effect on food quality and safety preservation (19, 29, 30). Currently, no food requirement driven approach is commercially used or available to help industry to use active packaging.

Moreover, regulatory constraints regarding solutions that imply solutes or volatiles migration (such technologies have to comply with both food and packaging regulation) create additional cost and delay before market uptake. In addition, there is a general consumers' widespread suspicion on sachets and emitters due to their possible interaction with the food product and misunderstanding of their role.

As regards the usage benefit, the reduction of food waste and losses achieved by using well-dimensioned packaging solutions, especially active packaging solutions, still need to be quantified and disseminated to all stakeholders in an informative and easy-to-understand manner, especially to consumers in order to increase their awareness and acceptance of such packaging as sustainable food packaging solutions.

Full assessment of environmental- and socio-economic benefits of *packaging solutions* is not straightforward. There is an urgent need of a holistic approach to tailor packaging materials, validate their usage benefit and increase end-users' acceptability. This could be achieved by (1) setting up a requirement-driven approach to globally deal with issues related to efficacy assessment, compliance with food and food contact material regulation, environmental constraints and consumer's acceptance and (2) driving a concerted and collaborative initiative including all relevant stakeholders (packaging producers, food companies, retailers, consumers) in the early stage of the deployment and validation of usage benefit of packaging solutions for increasing perceived benefits and awareness by all citizens.

The *high fragmentation* of today's innovation strategy in the packaging sector does not enable stakeholders to seize all opportunities for new food packaging solutions. There is an obvious lack of concentration between the numerous and diverse stakeholders throughout the whole packaging material life cycle, from the producers, food manufacturers to the waste managers. Particularly, the full assessment of the environmental benefit of eco-innovative solutions in terms of material (resources and waste) and usage (reduction of food waste and losses) is currently not achieved.

The adoption of eco-innovative packaging solutions by SMEs, that represent more than 90% of the EU food and packaging sector, is currently hampered by the fact that the large majority of these SMEs do not have a dedicated packaging manager and decision makers often lack the background knowledge, tools and network contacts regarding packaging issues that would otherwise enable them to move forward. To ensure competitiveness of EU SMEs, it is necessary to provide them with tools and reasoning that will enable them to enter and dominate this specific market of sustainable food packaging solutions where packaging solutions must be tailored to fit food and market specificities.

There is an urgent need to develop *early guidance tools* for packaging users and producers that will help them to *fast track* sustainable innovations up to market penetration. Based on *user-driven strategy* able to fit packaging to foods and market diversity, complexity and requirements, these decision-supporting approaches and tools should be able to design and communicate, in a user-friendly format, eco-innovative packaging alternatives by setting up, for instance, scores of sustainability performance. These calculated indicators could be a basis for the setting up of front-of-package sustainability labels, to be further disseminated to all end-users, especially consumers.

SOLUTIONS AND TOOLS TO ALIGN WITH THE PRINCIPLES OF CIRCULAR ECONOMY FOR FOOD PACKAGING

To address the main challenges listed above, there are some solutions, which are all underpinned by and aligns with principles of the circular bio-economy. Most of them are still in their infancy and some efforts are still needed to market them and enable the food packaging economy to create virtuous cycles instead of depletive ones and harness the whole innovation potential of research made in the field of food, material, environmental, and computer sciences.

In the following, the most promising solution in the development of bio-packaging solutions issued from the conversion of agro-food residues is presented. Then most recent developments, at the crossroads of food engineering and computer science, that allow to tailor packaging to food needs and to help users to select sustainable packaging solutions, are presented.

Converting Agro-Food Residues Into Innovative Bio-Packaging Solutions

The demand for bio-packaging solutions is growing worldwide. For instance, the European market for bio-based polymers (biodegradable or not) represents a current market value of almost € 4.5 billion, representing a CAGR (Compound Annual Growth Rate) of 21% and is estimated to increase to 2 M tons by 2020 (31). But this market remains very small with only 2% of the total polymer market. Among bio-based polymers, biodegradable polymer-based packaging represents only 0.8 M tons, € 2 billion (2016) (32). The main barrier to market uptake is attributed to technical bottlenecks related to the functional and production specificities of bio-based materials that are quite different from petrochemical plastics.

With the objective to convert agricultural and agro-food residues into "naturally biodegradable" packaging, microbial (bio-polyesters) engineered polymers enable a real environmental, economic and industrial added value by adopting regenerative process-oriented systems adapted to conventional and local industries. Among biodegradable microbial polymers, polyhydroxyalkanoates (PHA) and particularly the copolymer polyhydroxy (butyrate-co-valerate), P(HB-co-HV), are considered among the most promising substitutes of oil-based synthetic polymers (33–36) to tackle current negative externalities of our plastic packaging-more than 70% of accumulation of persistent plastic in the environment through landfilling and leakage (13). Among their advantages, they can be biologically synthesized using various feedstocks such as agro-food and urban by-products, residues and wastes, either liquid or solid. They are completely biodegradable in both natural (soil) and marine conditions, in contrast to other commercially available bioplastics (PLA, PCL, etc.) and a large number of copolymers displaying different functionalities can be produced by controlling the feedstocks and the microorganisms. However, currently available commercial grades [either P(HB-co-HV) or PHB] are still synthesized from noble food resources[5] using pure cultures of particular microorganisms (GMO origin) contributing to a prohibitive market price (about 5 €/kg) as compared to the one of conventional plastics. In addition, they display a limited range of hydroxyvalerate (HV) content (max. 3 wt%) that hinders their suitability for food packaging application due to high thermal sensitivity, low viscosity at the melting state, and low crystallization rate (37, 38). The FP7 EcoBioCAP project[6] demonstrated the feasibility, using food industry by-products as feedstock (olive wastewater or cheese whey) and mixed natural microbial cultures (MMC), of lab scale production of a P(HB-co-HV) with a HV fraction (in the range of 10–25%) higher than the current commercial grade (39–41). This higher HV fraction induces some polymer structural changes that can be advantageous to its processing and conversion into packaging (42, 43). Higher HV contents could be achieved using Volatile Fatty Acids (VFAs precursors) with a high propionic acid content. The incorporation of low cost lignocellulosic fillers stemming from lignocellulosic solid residues into P(HB-co-HV) permitted to tailor functional properties, especially water vapor and oxygen permeability, while decreasing the overall cost of the final bio-composite packaging material and maintaining its biodegradability (21, 22, 44, 45) (**Figure 2**). Incorporation of lignocellulosic fillers tends to decrease the ultimate tensile properties because of a lack of adhesion between the hydrophobic matrix and hydrophilic fibers (22). Globally, the mechanical properties are governed by that of the PHBV matrix which is, for the commercial grade with low HV content, too brittle to be used for flexible packaging application (**Table 1**).

To go further in the industrial deployment of PHA-based material, PHA conversion must be scaled-up based on the use of an optimized eco-efficient mixed microbial culture (MMC) based process. This allows to decrease investments and operating costs of PHA conversion with respect to pure culture and is made easier by using non-costly by products such as feedstock (35, 39). This type of process will enable the bioconversion of agro-food residues (no competition with food usage) into value-added material that is a better alternative use for bio-waste rather than only energy or compost. Municipal bio-waste could also be converted into PHA as is currently being explored in the framework of the RES-URBIS H2020 project[7] To enlarge P(HB-co-HV) industrial process ability and make it compatible with conventional packaging processing techniques, the HV content of the synthesized polymer must be controlled in a wide range using a combination of customized feedstock pre-treatment (acidogenic fermentation performed in conditions that trigger production of propionic acid in the VFAs mixture) and VFAs bioconversion into PHA. In addition, the combining of synthesized PHAs with low cost ligno-cellulosic fibers into bio-composites should continue to be explored to tailor cost and functionalities of PHA-based materials to food usage requirements as well as mechanical, transport, and cost properties.

Tailoring Packaging Properties to Reduce Food Waste and Losses

Packaging is a particular key player to improve food preservation, quality and safety conditions, and thus reduce food losses through, notably, setting up of Modified Atmosphere Packaging (MAP) technologies. In MAP, one of the main roles assigned to packaging materials is the control of mass transfer between the food, the packaging, and the atmosphere, i.e. ,permeation of gases from the surrounding atmospheres, absorption of these same gases (e.g., O_2 scavengers) or diffusion of active molecules voluntarily added in the packaging material (anti-microbial emitters).

MAP design is complex and requires knowledge on packaging material, food characteristics, and optimal gases composition and is thus dependent on the product (10, 11, 46). In the case of passive MAP, Tailorpack (http://plasticnet.grignon.inra.fr/IateTools/TailorPack) is an example of a user-friendly software able to design packaging for fresh produce such as fruit and vegetables. A mass balance of gases composition in the headspace is done by taking into account the permeation of the gases through the film via Fick's first law and the respiration of the fruit modeled using Michaelis and Menten's law (10, 28, 47). For MAP of non-respiring fresh products (e.g., meat, ready-to-eat food products, etc.) similar tools exist that help the user to choose the suitable packaging material and atmosphere composition to limit growth of pathogens (48, 49). However, these tools are limited to some specific food applications.

Among the latest developments in antimicrobial emitters, a promising way to develop indirect contact anti-microbial packaging is the use of volatile compounds, encapsulated in RH-sensitive macromolecules that prevent release during storage in dry conditions. Once exposed to moisture, release of the molecule is triggered and then diffuses into the headspace toward the food surface where microbial growth usually takes place (50, 51). Although widely available on the Asian market (see for example the AITC-based Wasaouro™ film[8], they are almost inexistent on the EU market (27, 52, 53) because of more restrictive EU regulatory requirements (54) and difficult efficacy optimization (55) principally due to the complexity of the RH-triggered release mechanism. Among volatiles, organic aroma compounds from essential oil extracts such as allyl isothiocyanate (AITC) from

[5]see for example the most widely available production of the Chinese company, Tianan synthesized from glucose syrup.
[6]EcoBioCAP FP7 (2011–2015) ECOefficient BIOdegradable Composite Advanced Packaging (2011–2015).
[7]RES-URBIS H2020 (2017–2019) REsources from URban BIo-waSte.
[8]Mitsubishi-Kagaku Foods Corporation. Wasaouro™ products. http://www.mfc.co.jp/wasaouro/e/products/

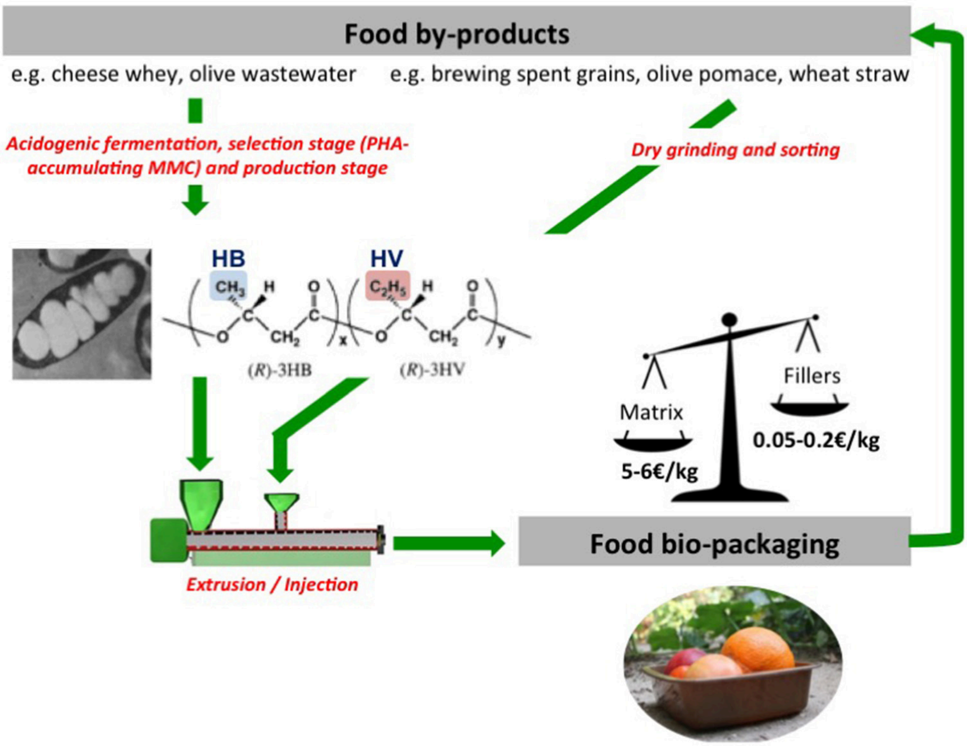

FIGURE 2 | Microbial engineered polymers (example of PHA) permit conversion of food by-products into food bio-packaging (EcoBioCAP FP7 2011–2015).

mustard or carvacrol from oregano, have been proved to be particularly efficient on main microorganisms (56–58) at doses that are below the detection threshold by sensory panel. Recently, setting up dedicated mathematical algorithms that predict the complex diffusion-reaction system and kinetic release toward headspace, Kurek et al. (51) tailored active biodegradable material in such a way that it complies with the food requirements (**Figure 3**).

The next step of a requirement driven approach to design packaging materials will be to consider, at the early stage of their scaling up, all the food, consumer, market, and legal requirements that the material should fulfill. In the specific case of active packaging, when volatiles are emitted toward the food, consumer exposure, including all sources of the substance of concern such as natural occurrence in food products must be considered in addition to food needs in terms of quality and safety preservation and shelf-life extension. Indeed, for active packaging solutions to be commercially viable and successfully adopted by the market, it is necessary to ensure that they meet the regulatory requirements while ensuring intended efficacy and limited impact on food sensory properties (especially for volatiles also used as flavorings). In particular, to validate the fact that active materials have, in operational conditions, a final beneficial outcome in terms of usage benefit that outweighs the possible extra expenses of adding the new technology, it is necessary to demonstrate their positive role to decrease food waste and thus contribute to increase sustainability of the food packaging system as a whole.

Early Guidance Tool to Develop and Select Sustainable Packaging Solutions

For almost a decade now, Europe has been investing a lot in research for new developments in packaging technologies and was perceived as a powerful market with an immense potential demand[9]. All forecasts showed a dramatic growth in production, use and acceptance of bio-, and smart packaging technologies for 2000–2010, but these figures have proved to be very optimistic. Even though several new technologies were successfully developed at lab-scale all around Europe (more than 15,000 scientific papers dealing with bio-, and active technologies were published on the 2010–2015 period, **Table 2**), they never or very rarely reached the market (>500 exploited patents over the same period). Many factors have contributed to this failure including the resistance of the food industry and consumers to adopt unknown technologies, the costs of the new implementation, the inefficiency and lack of competitiveness of the new technologies and regulatory barriers. But the biggest challenge remains the lack of collaboration and exchange between stakeholders of the food chain (R&D centers, food and packaging manufacturers, legislators, consumers) resulting in lab-scale prototypes that, though efficient, never meet market expectations in their entirety, in terms of potential applications,

[9]Pira International, 2009; Research And Markets, 2010. The Freedonia Group, 2011.

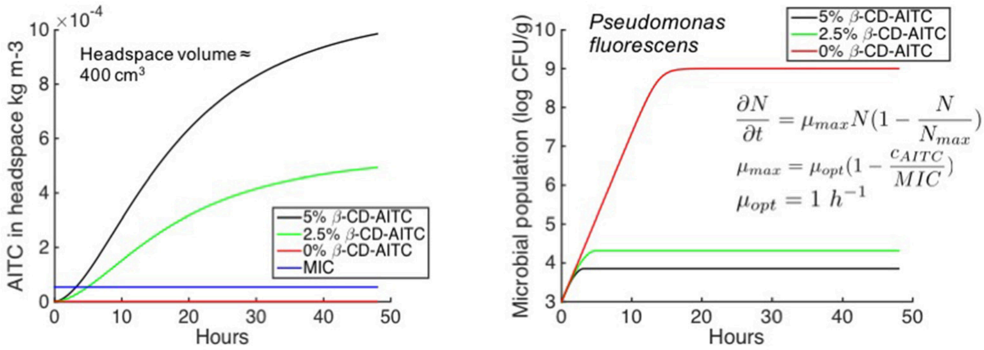

FIGURE 3 | Prediction of the AITC active compound release (on the left) toward headspace as a function of quantity of active compound added in the formulation of the packaging and correlated predicted effect on the growth of *Pseudomonas fluorescens* (on the right) [adapted from (51)].

TABLE 2 | Overview of the current innovation status in the sustainable food packaging sector.

Period: 2010–2015	Active AND packaging	Biopolymers AND bio-based AND bioplastics
Nb of scientific publications*	8,250 (900 in 2015)	11,000 (1,400 in 2015)
Nb of patents**	89 (11 in 2015)	754 (26 in 2015)
Nb of exploited patents***	53 (6 in 2015)	452 (15 in 2015)
Current deployment ratio****	1%	4%

*From the Web of Science.
**Worldwide database/Espacenet.
***calculated from the paper of Giuri et al. (59) that claims that about 40% of patents are not used taking all sectors into consideration.
****Ratio of exploited patents on papers.
Something missing in table above—Active AND …… packaging.

added-value, risk-benefit balance, compliance with EU rules or consumer trust.

The efficiency of new packaging solutions to reduce the overall environmental impact of the food/packaging system is never assessed on large-scale market nor communicated in easy-to-understand format to end-users. Thus, almost 50% of the food and packaging industries specialists are not fully aware of new available technologies (60). The situation is similar for consumers: they are generally not aware and are generally skeptical regarding new technologies that they do not fully understand, especially active packaging (e.g., Actipak final report) (61–63).

Moreover, the food and packaging industries encompass a large number of SME's, which face specific difficulties through not having sufficient in-house technical resources and needing to rely on suppliers for advice. Fully efficient advice resulting in a direct implementation of new technology in SMEs is rarely available as expertise on packaging innovations is fragmented, based on a lot of, multi-disciplinary knowledge owned by many different actors (raw material suppliers, food manufacturers, distributors, researchers). As a result, SME's may not always be using the best and most sustainable food packaging solution. In the framework of the FP7 EcoBioCAP project, the first lab prototype of a multi-criteria decision software for modified atmosphere packaging of respiring fruits and vegetable has been developed together with an argumentation-based tool for management of conflicting viewpoints between preferences expressed by the involved parties (64–67). They help to handle the complex decision in the field of packaging choice and design considering only a restricted range of criteria at the moment (**Figures 4**, **5**).

By proposing in depth information about eco-innovative packaging technologies such as value-added, consumer acceptance, sustainability performance, up-scaling ability, etc. the next generation of Decision Support System (DSS) should provide unique and specific guidance to food and packaging SMEs in terms of technical assistance for the selection among eco-innovative packaging alternatives. It is a necessary evolve to a wider acceptance and assurance that these organizations will remain competitive. To the best of our knowledge, this tool does not exist yet in the food packaging sector.

WHICH IMPACTS SHOULD BE EXPECTED BY 2050?

The next generation of food packaging should significantly contribute to reduced waste in both food and packaging materials, and its negative impacts on the environment (e.g., resource utilization, greenhouse gas emissions, pollution) by 2050.

Indeed, the carbon footprint of food produced and not eaten (around 100 million tons annually in the EU) is estimated to be equivalent to 495 million tons of CO_2. Globally, the blue water footprint (i.e., the consumption of surface and groundwater resources) of EU food wastage is about 37 km^3, half the volume of Lake Geneva. Produced but uneaten food occupies almost 210 million hectares of land. Modeling suggests that, if nothing is done, food waste could rise to over 200 million tons by 2050 (68, 69).

In the meantime, 23 million tons of plastic packaging are produced each year at European level (92 million tons expected in 2050). If production and use continue within the current linear framework, worldwide, by 2050 the plastic industry will represent 1,124 million tons of plastic materials, 20% of total oil

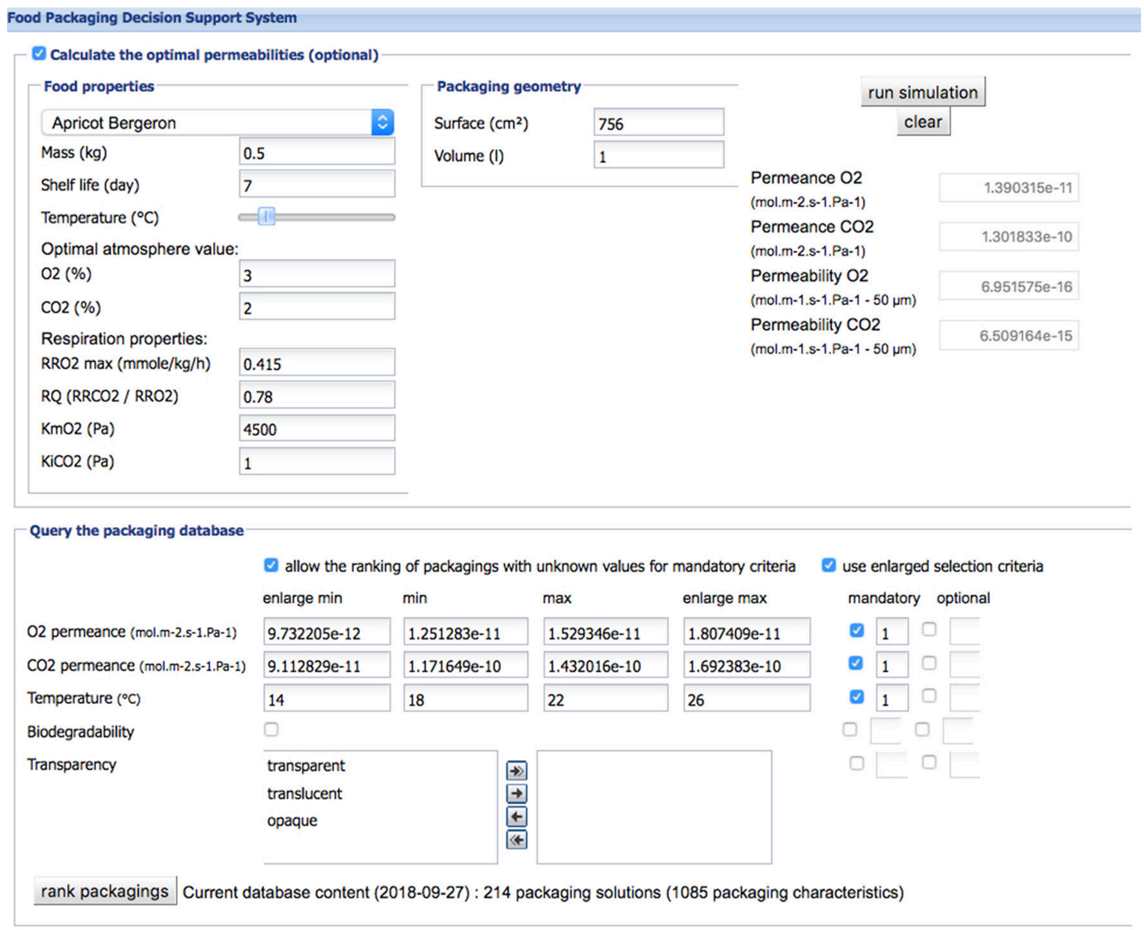

FIGURE 4 | Main window of the DSS EcoBioCAp with indication of the values of permeances calculated for the case study Apricot and building of the multi-criteria query.

consumption, 15% of carbon budget[10] and if nothing is done there may be more plastic than fish in the ocean, by weight (13).

By promoting market uptake of packaging innovations enabling extension and better management of food shelf-life, 50% decrease of food waste at the retail and consumer level could be expected by 2050, i.e., saving about 100 million tons of food which corresponds to an absolute decrease of 250 million tons of CO_2-equivalent, about 18 km^3 of water resources and 100 million hectares of land recovered (70). This achievement is in line with the EU targets[11]

If one in two food packs are made of a “bio-benign” material by 2050, 50% of packaging waste reduction could be achieved, i.e., about 46 million tons of plastic waste less, reducing the negative impacts of plastic accumulation in natural systems and the long term adverse effects expected.

By substituting one pack out of two with organic waste-based packaging, net saving of about 43 MTOE of virgin oil based resources is expected on average by 2050 at European level and more than 150 MTOE on a global level. These savings represent an absolute reduction of GHG emissions of 120 million tons of CO_2-eq[12] at EU level and 500 million tons of CO_2-eq worldwide (direct CO_2 emissions only).

In summary, at European level, expected reduction on both food and packaging waste, thanks to sustainable food packaging solutions, would correspond to a net reduction of 370 million tons of CO_2-eq, representing a net saving of about 10% of GHG emission according to 2050 EU objective to be consistent with the 2°C limit (IEA 450 scenario, EEA greenhouse gas–data viewer).

The next generation of food packaging will support the transition from a linear to a circular economy.

Our current plastic-based food packaging economy is an iconic linear application (**Figure 6**): from the 78 millions of tons of plastic packaging produced each year at European level, 98% originates from virgin oil-based feedstock, and after-use, only

[10]Energy used in production and carbon released through incineration and/or energy recovery after-use (i.e., 20% in 2050). Carbon budget based on 2 degree scenario.

[11]http://www.un.org/sustainabledevelopment/sustainable-consumption-production/

[12]1 toe 11630 kWh and 0.24 kg CO_2/kWh.

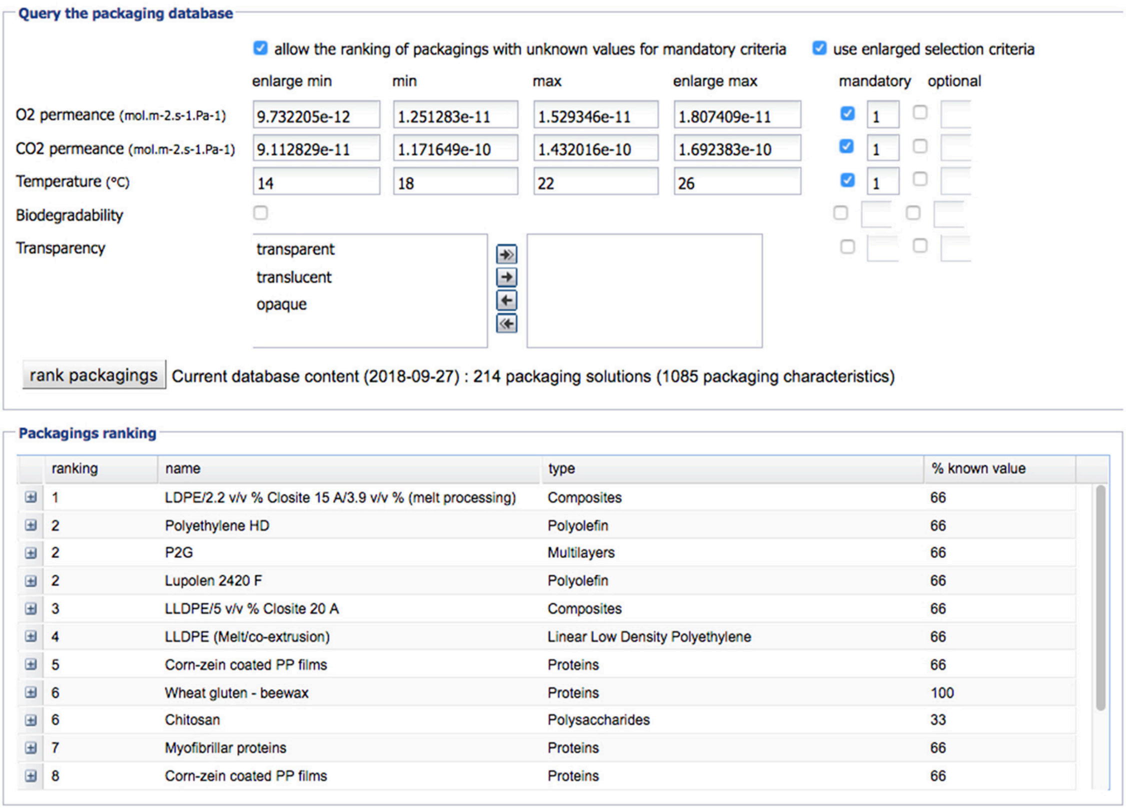

FIGURE 5 | Ranking of the most suitable packaging solutions proposed by the DSS EcoBioCAP for the case study "Apricot".

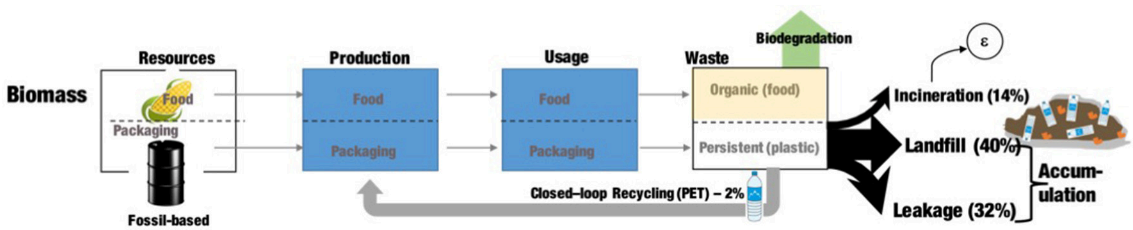

FIGURE 6 | Current linear status of today's food packaging economy [data from (13)].

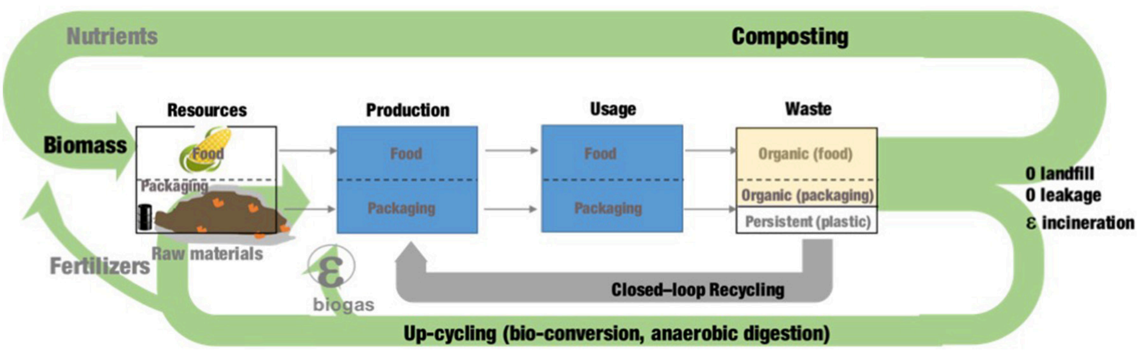

FIGURE 7 | Unlocking the circular economy potential of the food packaging chain, a prospect for the future.

14% is recycled, far below the global recycling rates for paper (58%)[13]and iron and steel (70–90%) (71). Forty percent of plastic packaging is still put in landfill and more than 30% leaks into natural systems (especially oceans). If the current strong growth of plastics usage continues as expected, the consumption of oil resources by the entire plastics sector will account for 20% of the total oil consumption by 2050 (13). Currently 8 million tons of plastics leak into the ocean each year worldwide for a total amount of 150 million tons of plastic waste in the ocean (14), 62% of it is packaging.

If recycling has been seen as essential to the setting up of an effective after-use plastics economy, safety and environmental issues of closed-loop recycling[14] (e.g., bottle-to-bottle for PET) and lack of resilient secondary markets for cascaded recycling[15](recycling of plastics into other applications than food packaging) level off its development to the current low level. On the whole almost half of PET is not collected for recycling, and only 7% is recycled bottle-to-bottle (72).

The thermo-mechanical recycling as is currently applied in bottle-to-bottle technologies, entails a deterioration of the material properties by damaging or shortening the polymer chains of the PET and the presence of contaminants and impurities from pre-use and degradation products of monomers and additives, resulting in a down-cycling[16]of the material (73). The safety of recycled plastics for food contact, by nature, needs the recovery of virgin material that could not be achieved with low environmental cost using current methodologies (74, 75). Recycling is not the unique solution to be deployed to solve the plastic economy issue. Alternative packaging solutions must be deployed.

Aligned with circular economy principles, by converting the unavoidable part of organic wastes into new materials (100% biodegradable bioplastics), the next generation of bio-waste based materials will create an innovative, more resilient and productive waste-based food packaging economy by decoupling the food packaging industry from fossil feedstocks and permitting nutrients to return to the soil (**Figure 7**).

More especially, we can imagine by 2050, being able to produce 50% of the European food packaging materials from renewable, non-food resources by using up-cycling of organic (food and packaging) wastes, the other 50% oil-based materials being closed-loop recycled. This bio-based packaging (about 46 MT by 2050) will be fully biodegradable and home-compostable (100 million tons of organic food and packaging waste could be converted into up to 50 million tons of compost) solving current issues of persistent plastic waste accumulation in line with EU Circular Economy Strategy (e.g., banning of landfilling by 2050).

In the meantime, the use of these organic residues in an up-cycling loop through bio-conversion processes (aerobic accumulation, anaerobic digestion, etc.) will allow to produce new materials (bioplastics), energy (to be reused for the food and packaging production steps), and ultimately some fertilizers (76).

By shifting our current food & packaging industry to a circular economy development path would generate annual total benefits of up to € 0.6 trillion in Europe (estimated from data given in Growth Within: A Circular Economy Vision for Competitive Europe (77).

[13]International Council of Forest and Paper Associations, Statement on Paper Recycling (2014).

[14]Recycling of plastics into the same or similar-quality applications.

[15]Recycling of plastics into other, lower value applications.

[16]Converting waste materials into new materials or products of lesser quality and reduced functionality.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the present review. PB supervised the decision support tool presented in **Figures 4**, **5** with associated database. SG performed the mathematical modeling part. VG wrote the first draft of the manuscript. HA-C, NG, SG, VG, PB, and CF wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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REVIEW
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Potentialities and Limits of Some Non-thermal Technologies to Improve Sustainability of Food Processing

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In the whole food production chain, from the farm to the fork, food manufacturing steps have a large environmental impact. Despite significant efforts made to optimize heat recovery or water consumption, conventional food processing remains poorly efficient in terms of energy requirements and waste management. Therefore, in the few last decades, much research has focused on the development of alternative non-thermal technologies. Some of them, such as membrane separation processes, hydrostatic or dynamic high pressure, dense phase or high-pressure carbon dioxide, and pulsed electric fields (PEFs) have been extensively studied for cold pasteurization, concentration, extraction, or food functionalization. However, it is still difficult to evaluate the actual advantages or limits of these innovative processing technologies to replace conventional processes. Thus, the overall aim of this paper is to present an overview of the most relevant studies dealing with the potentialities and limits of these non-thermal technologies to improve sustainability of food processing. After a brief presentation of the physical principles of these technologies, the paper illustrates how these technologies could play a decisive role for sustainable food preservation or valorization of raw materials and by-products.

Keywords: non-thermal technologies, sustainability, food processing, high pressure, membrane processes

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INTRODUCTION

As clearly expressed in the 2030 agenda for sustainable development of United Nations, the global food system is directly or indirectly linked to most of the sustainable development goals proposed to promote and plan sustainable development worldwide (1). The challenge in the coming decades will be to ensure the availability of sufficient safe, nutritious, tasty and convenient food to the rapidly expanding and more affluent population while achieving sustainability (2, 3). At the present time, the global food system, composed of many sequential steps from agricultural production to consumers, is characterized by different sustainable weaknesses which still remained evaluated from limited number of common indicators, even if some recent studies proposed now multi-indicator analysis (4). The environmental impact of agricultural production was particularly investigated, showing among other things, that it is responsible for ∼1/4 of all greenhouse gas emissions from human activities (5). In addition, ∼25% of water consumption worldwide was attributed to food processing, and it is also responsible for the highest contribution to the emissions of organic water pollutants (6, 7). Moreover, ∼30–50% of produced foods become waste (8), fruits, vegetables, cereals, and cereal products contribute the most to the food loss and waste throughout the food supply chain (9). Aquatic, atmospheric and solid waste generation characterizes the impact of food processing on the environment, and the improvement initiatives are consequently shift toward three main axes: energy consumption, solid waste reduction or up-cycling, water consumption, and wastewater reduction. Obviously, other drivers influence the efforts engaged: environmental legislation has to be respected and complex consumer choice and preference has to be foreseen before implementing alternative products or services (10). Besides, the increase in energy prices typically leads food manufacturing companies to invest in a better energy management. With respect to the latter point, thermal processes (pasteurization, sterilization, evaporation, refrigeration, freezing, and drying) are characterized as the most energy-consuming technologies in the food industry. But the conventional thermal processes are directly in line with one of the priorities concerning food processing: food safety—which requires processing steps to decrease microbial loads and consequently enhance safety and shelf life.

The development of green technologies in the food manufacturing sector is particularly relevant with the objective to convert raw agro materials into food products with the desired quality and functional properties while increasing manufacturing efficiency. In addition, companies will have to remain competitive at a time when consumer and government demands for sustainable development are constantly increasing (11, 12). Specifically, non-thermal processes recognized as value-added technologies have gained importance the last few decades as sustainable alternatives to conventional food processing—through direct reduction of energy and water consumption during processing, but also by reducing energy impact during storage. The indirect effects of non-thermal processing are also expected as a contribution to solid waste reduction and valorization of biomass resources (11, 13). The indirect impact of non-thermal processing on food processing sustainability could be even larger than direct impacts, since food losses, suboptimal utilization of by-products/processing residues and unnecessary quality decay within the supply chain are major inefficiencies within the food manufacturing sector.

Several emerging high-potential technologies, including high pressure (high hydrostatic pressure (HHP) and dynamic high pressure), pulsed electric field (PEF), and carbon dioxide processing, as well as membrane processing (which is already well-established), are all discussed in this paper to illustrate the potential impact of non-thermal food processing technique on improving the sustainability of food processing operations. These technologies are based on physical or chemical constraints, and have the particularity to be efficient at mild temperatures compared to conventional food processing operations used in industry to stabilize food products or extract compounds of interest (14).

The purpose of this review is to provide an overview of the current status and trends dealing with the potentialities and limits of these selected non-thermal technologies. The review intends to present and compare these different technologies according to three applications closely linked to food processing sustainability: stabilization, extraction and water recovery, and food waste management.

OVERVIEW OF PRINCIPLES AND TECHNOLOGIES

High Hydrostatic Pressure

Treatments by HHP consist in placing the product (liquid or solid) in a pressure vessel filled with the pressure-transferring medium (PTM) (generally water in food applications) that is compressed by a pump (**Figure 1**). Based on the Pascal or isostatic principle, the hydrostatic pressure is transmitted uniformly and immediately to the sample through the PTM. One of the major advantages of this technology, compared to heat treatments, is that the effects of pressure are not dependent on the size and geometry of the products. However, the classical limitation of heat transfer has to be taken into account. The adiabatic heat of compression is reversible and estimated to about 3°C per 100 MPa for most of foods and can reach 8–9°C/100 MPa for high-fat products (15). Hence, after pressure release, the product will return to its initial temperature (15). The three processing parameters characterizing an HHP treatment are the temperature, the pressure, and the exposure time. Generally, in the food preservation area, pressure levels between 100 and 800 MPa are applied, at mild a temperature (4–20°C), from several seconds up to several minutes (16). In the food industry, the treatment vessels typically have an internal volume ranging from 50 to 525 L. The efficacy of high pressure (HP) on biological systems is governed by Le Chatelier's principle, which provides that pressure will favor any phenomena (reaction, transition…) accompanied by a reduction in volume and will inhibit those associated with a volume increase. Due to the low compressibility of covalent bonds as compared to weak energy bonds, low molecular weight molecules, such as aroma compounds, vitamins, and minerals are rarely impacted by HP, while macromolecules, such as proteins and starch, can change their native structure (16). Historically HHP treatments have been mainly applied to food preservation, but new promising applications in food or biotechnology areas have been studied the last several last years (17–19). Barba et al. (17) present a review of the potentialities of new HHP applications, which include: (a) recover health-related compounds, (b) improve health attributes of foods through increased bioavailability of micronutrients and phytochemicals, (c) reduce allergenic potential, (d) preserve healthy lipids, (e) reduce salt intake by increased saltiness perception, and (f) reduce formation of processing contaminants (17).

High Pressure Homogenisation

For the last decade there has been a growing interest focused on the development of dynamic high-pressure processing, i.e., (ultra)-high pressure homogenization, in food processing. Various applications of this novel non-thermal processing technology have been specifically designed with a sustainable

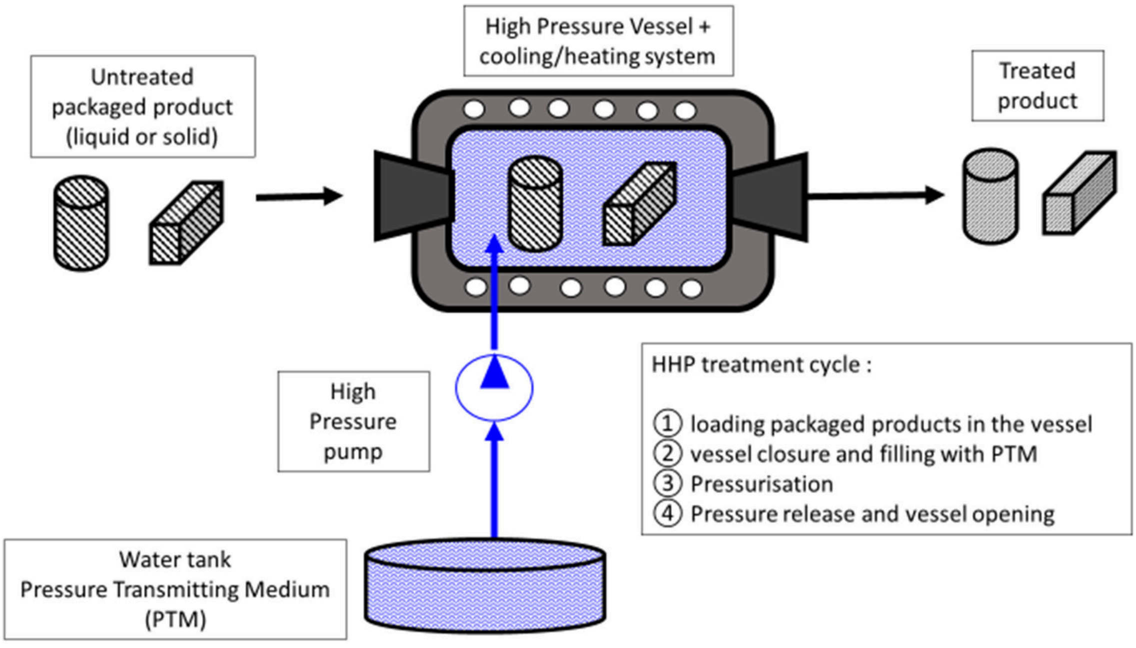

FIGURE 1 | Schematic layout for a High Hydrostatic Pressure (HHP) treatment pilot.

development perspective in mind. This eco-friendly continuous processing method is liquid based, and generates a combination of physical, hydrodynamic, and thermal effects allowing for the extraction of natural compounds from suspended particles, the non-thermal stabilization of liquid foods, such as milk or juice, but also the production of extremely stable submicron emulsions (20, 21). Dynamic high-pressure processing consists of pressurizing the liquid to treat for ∼10 s using a high-pressure generator, and then the fluid is forced through a high-pressure valve characterized by a very small orifice up to 2 µm (**Figure 2**). According to the nominal pressure level, the process is deemed High pressure homogenisation (HPH) (100–200 MPa) or UHPH (300–400 MPa). When the pressurized fluid is forced through the HP valve, the pressure drops from high pressure down to atmospheric pressure, thus inducing a significant increase of the fluid velocity. This is associated with intense shear rates. At the same time, the kinetic energy is partially converted into heat, inducing a short-life heating phenomenon (∼ <1 s). Dynamic high pressure is recognized as a non-thermal or mild thermal processing since the temperature increase is limited in the amplitude and can be easily controlled by a cooling system located just after the HP valve. After the valve-gap, the fluid flows in the chamber where turbulences, cavitation, and impacts between particles and against walls occur, as well as recirculation. At the present time, UHPH has potential as a more sustainable food processing operations, as defined by Chemat et al., and has been demonstrated at pilot scale, but upscaling to transfer the technology to industrial processing lines is just being implemented now (11). A large number of studies have been carried out to demonstrate the advantage of UHPH compared to classical processes in terms of process effectiveness, but very few studies have been dedicated to quantify the environmental impacts of UHPH (22).

Carbon Dioxide Processes

Carbon dioxide is a cheap, non-toxic and non-flammable compound which has been intensively studied in food processing for the purpose of pasteurization and sterilization, product texturing and functionalization, as well as for fractionation and extraction of compounds (23–26). These processes generally consist in mixing carbon dioxide under gas, liquid or supercritical state into a liquid or solid matter and maintaining a pressure/temperature condition during a sufficient period to allow for matter transfer between both (**Figure 3**). Among processes involving CO_2, the most common are CO_2 acidification (or carbonation), Dense Phase Carbon Dioxide (DPCD), High Pressure Carbon Dioxide (HPCD), and Super Critical Carbon Dioxide treatment (SC-CO_2). **Figure 4** and associated **Table 1** illustrate a selection of effective pressure and temperature treatments related to these goals (27–47). Treatments, such as DPCD, HPCD and SC-CO_2 often have overlapping pressure/temperature ranges (e.g., DPCD and HPCD can be used for CO_2 under liquid phase). Moreover, similar technologies and applications can be identified by one or more of these names. Hence, four domains are often distinguished according to the targeted effect of the treatment (**Figure 4**): destabilization of the native structure of pH-sensitive proteins, inactivation of vegetative microorganisms, solubilisation of non-polar (or low polar) compounds in SC-CO_2, and inactivation of endospores. As only few data can be found on the cost of these treatments (26), as a first approximation it can be assumed that the energetic cost increases when temperature and pressure

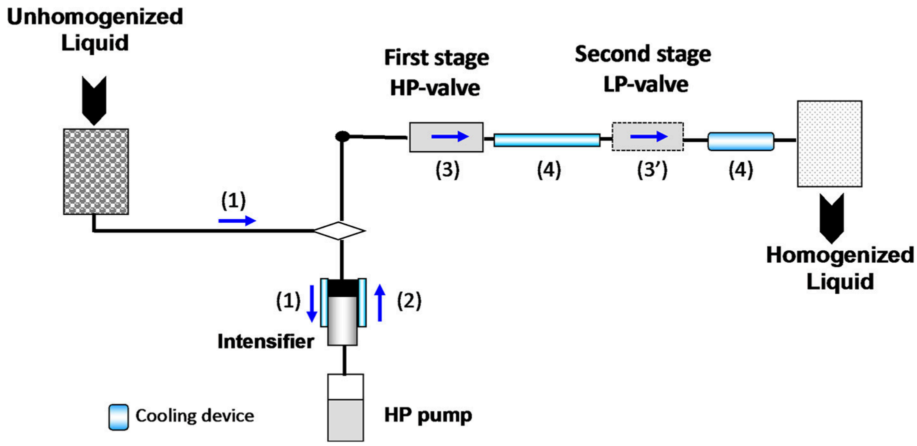

FIGURE 2 | Schematic layout for ultra-high-pressure homogenization (HPH) pilot. Unhomogenized liquid is pumped to the high-pressure intensifier (1), pressurized (2) and forced through high pressure (HP) then low-pressure (LP) valves (3–3′). Fluid temperature heating is limited by cooling devices (4).

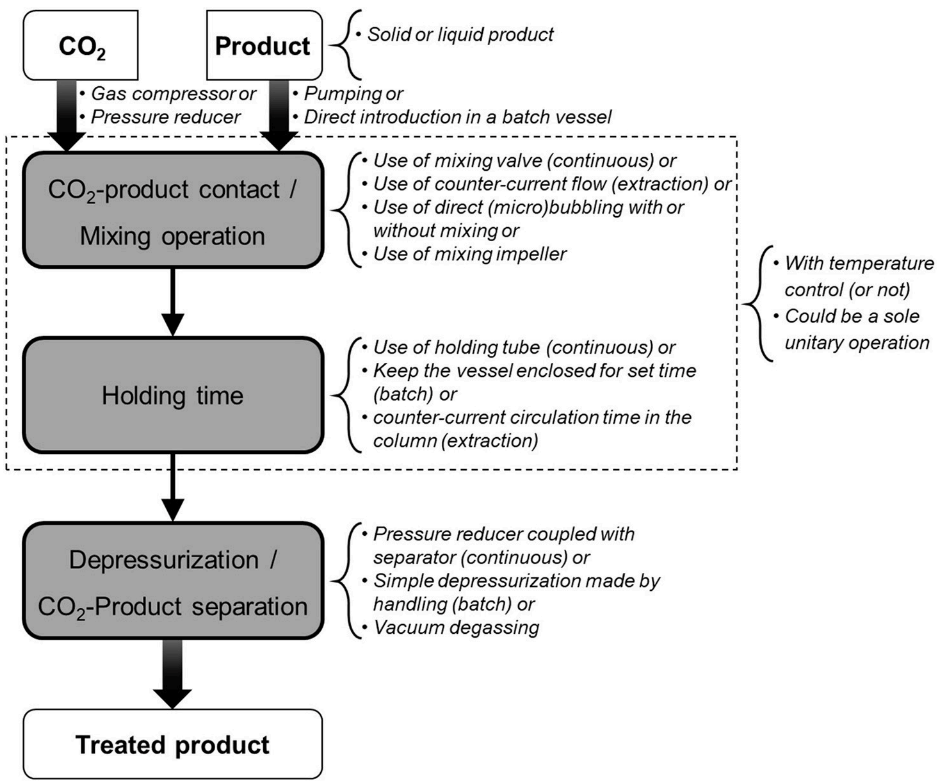

FIGURE 3 | Steps and technical characteristics of CO_2 treatments reported in **Table 1**.

increase. Nonetheless, for the range of applications considered (stabilization of a product, extraction, etc.), processes using CO_2 are considered green processes, as they represent an alternative to thermal treatment, high pressure (above 200 MPa) treatment, and solvent extraction (25, 26). These processes do not generate CO_2 but use existing resources, which is an important point for sustainability requirements (26).

Pulsed Electric Fields

PEF is based on the application of short electric pulses (usually 1–20 µs, but with a range of 50 ns to several milliseconds) with a high field strength (15–80 kV·cm^{-1}) to samples placed between two electrodes. This can be done in a batch or continuous treatment chamber (**Figure 5**). PEF is considered a non-thermal processing method as well. If a biological cell is exposed to a

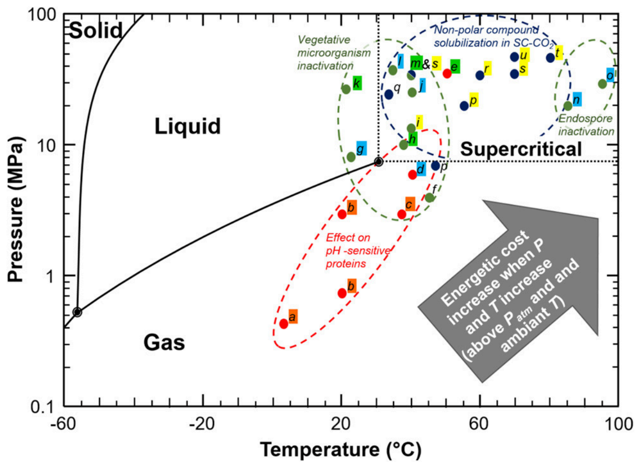

FIGURE 4 | Representation of effective CO_2 treatments on a phase CO_2 diagram. Lettering is described in **Table 1**. Coloured highlight indicates the name of the different CO_2 treatments as mentioned in the corresponding studies: Orange, CO_2 acidification (carbonation); Blue, HPCD; Green, DPCD; Yellow, SC-CO_2.

sufficiently high electric field, its membrane becomes permeable to molecules that otherwise cannot pass through; this behavior is referred to as "electro-permeabilization" or "electroporation" (49–51). Depending upon process parameters (essentially electric field strength and pulse duration) and total energy input, PEF applications can be divided into different types: microbial inactivation (15–40 kV/cm to 1,000 kJ/kg); sludge disintegration (10–20 kV/cm to 50–200 kJ/kg); improvement of mass transfer in plant or animal cells (0.7–3.0 kV/cm to 1–20 kJ/kg); reversible electro-permeabilization of biological cells for DNA transfer (0.7 kV/cm to 1–10 kJ/kg); induction of stress response (0.5–1.5 kV/cm to 0.5–5 kJ/kg) (15). Examples of applications and experimental conditions of PEF for different food processing techniques have recently been reviewed by Barba et al. (52) and Chemat et al. (11).

Membrane Processes

Membrane separation processes are also good candidates to achieve more sustainable food processing operations. Indeed, membrane systems can be operated in continuous mode, which limits start up and shut down as well as cleaning procedures and leads to consistent product quality. Working temperatures are low (i.e., ambient or temperatures <0–80°C) without involving phase changes or chemical additives; the qualities of heat-sensitive products are thus preserved, so waste generation as well as energy costs are limited. Furthermore, they can be used to achieve various objectives of separation (i.e., concentration/clarification, purification, fractionation, and extraction) but can also permit the recovery and reuse of by-products for a more effective utilization of raw materials. Finally, they are modular and thus easy to scale up. All these advantages make them one of the most promising technologies in terms of sustainable processes (53, 54).

At the heart of all membrane processes, the membrane acts as a thin selective barrier or interface between two phases, and which ensures the transfer of solvent and/or solutes due to a driving force (**Figure 6**) (i.e., pressure gradient in microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), concentration gradient in pervaporation (PV) and membrane contactors (MC), electrical potential gradient in electrodialysis (ED), or temperature gradient in membrane distillation (MD). According to the specific membrane properties (e.g., nature (organic or inorganic) structure (dense or porous), etc.) the separations result from different mechanisms (sieving, charge, or diffusion effects) allowing different processing objectives to be achieved (57).

Of course, other processes are also considered potential candidates for green technologies (e.g., ultrasound, microwave, Instant Controlled Pressure-Drop, etc.). However, this review paper is limited to establishing an inventory of the benefits and energetic treatment costs for the five aforementioned processes with respect to food stabilization, extraction, and water recycling.

NON-THERMAL STABILIZATION

The stability of food products over time is certainly one of the most important considerations of quality for food manufacturers. To ensure this stability, food manufacturers have to target different goals such as:

- limiting microbial growth in food during storage by direct inactivation of microorganisms, or by generating conditions limiting their growth (such as acidification),
- maintaining (or increasing and then maintaining) the nutritional quality of the raw material by limiting/controlling foodstuff denaturation during processing, and then limiting enzymatic alteration (the most often by direct inactivation during the process) or oxidation (by limiting formation of reactive oxygen species),
- avoiding any dephasing or exudate release by appropriate texturization.

The five alternative processes reviewed in this paper have demonstrated their effectiveness to stabilize various food stuffs by achieving the objectives of stability described above. Indeed, many papers show that these alternate processes can result in comparable or even better stability than traditional thermal processes, but with comparable or lower energetic costs.

Hydrostatic High Pressure

High hydrostatic pressure has been applied to food preservation since 1980–1990. It is widely reported that HHP treatments above 350 MPa permit the inactivation of spoilage microorganisms and enzymes at low temperatures, and can also induce the denaturation of macromolecules, such as proteins, lipids, and starch (18, 58–60). Cell membranes are often considered the first site of injury in pressure-inactivated microorganisms. Even if the exact inactivation mechanisms are not yet fully understood, experimental data show that HHP affects cell membrane permeability and cellular structures, probably through alteration of proteins and lipids (19). As

TABLE 1 | details about the CO_2 processes described in **Figure 4**.

Label	Application		Process name in the original paper	Raw material considered	Parameters *P* (MPa) / *T* (°C) / *t* (min)/Other	Targeted effect and result		Source
a	Effect on proteins aiming at	- Functionalize	Carbonation	Milk	0.32/4/45	Vectorization of a casein fraction		(27)
b		- Fractionate/extract	CO_2 acidification	Soy flour proteins dissolved at pH9 (½ diluted)	∼0.7/20/∼20 ∼3/20/∼20	Soy proteins aggregation and separation	11S fractio 7S fraction	(28)
c		- Extract	CO_2 acidification	Sponge	3/37/13.5	Collagen and gelatine solubilisation	12.4% yield	(29)
d		- Texturize	HPCD	Water solution/silk	6/40/120	Silk protein gelation		(30)
e			DPCD	Myosin	20/50/<1	Myosin gelation		(31)
f	Pasteurization		Low-pressure CO_2 microbubbles	Milk	4/45/5	*E.coli*	3.0 Log_{10}	(32)
g			HPCD	Fresh cut carrot	8/22/10	Total coliform	5.0 Log_{10}	(33)
h			DPCD	Carrot juice	10/37/45	*S. typhimurium*	3.3 Log_{10}	(34)
i			SC-CO_2 pasteurization	Fresh cut coconut	12/40/15	Vegetative bacteria and yeasts	2–3 Log_{10}	(35)
j			HPCD	Milk	25/40/50	Yeast population	3.0 Log_{10}	(36)
k			DPCD	beer	26.5/21/4.77	Yeast population	7.4 Log_{10}	(37)
l	Pasteurization and enzyme		HPCD	Orange juice	38/34/10	*S. typhimurium/L. monocytogenes*	>6.1/>6.4 Log_{10}	(38)
m	inactivation		DPCD	Red grapefruit juice	34.5/40/7	Total aerobic cultivable bacteria	5.1 Log_{10}	(39)
n	Sterilization		HPCD	Bacterial suspension	20/85/30	*B. subtilis* spores	1.3 Log_{10}	(40)
o			HPCD	Bacterial suspension	30/95/120	*B. stearothermophilus* spores	5 Log_{10}	(41)
p	Non-polar (or low polar) compound extraction		CO_2 expanded-etOH SC-CO_2 extraction	*Haematococcus pluvialis*	7/45/120 /∼50% eth. 20/55/120	Astaxantin extraction	124% yield 2.5% yield	(42)
q			SC-CO_2 + co-solvent	Plant coproduct	25/33/60/∼50% eth.	Terpene and resin	9% yield	(43)
r			SC-CO_2 extraction	Plant coproduct	34.5/60/30	Terpene and resin	5% yield	(44)
s			SC-CO_2 extraction	*Spinacia oleracea* L.	35/70/360 35/40/360	Carotenoid Polyphenol	Max yield Max bio-activity	(45)
t			SC-CO_2 extraction	Dehulled palm kernel	48.3/80/40	Palm kernel oil	49 g/100 g	(46)
u			SC-CO_2 extraction	*Euterpe oleracea*	49/70/30	Berry oil	45.37% yield	(47)

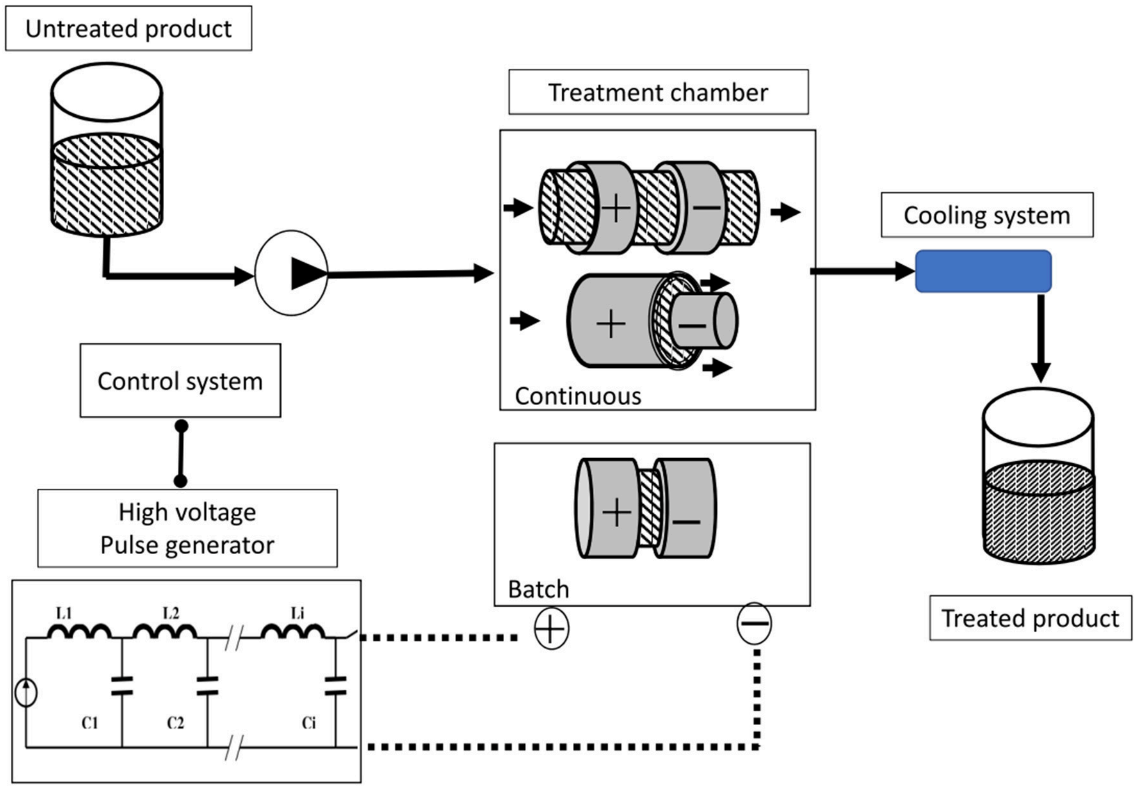

FIGURE 5 | Schematic layout for a Pulsed Electric Fields (PEF) treatment pilot [adapted from Picart and Cheftel (48)].

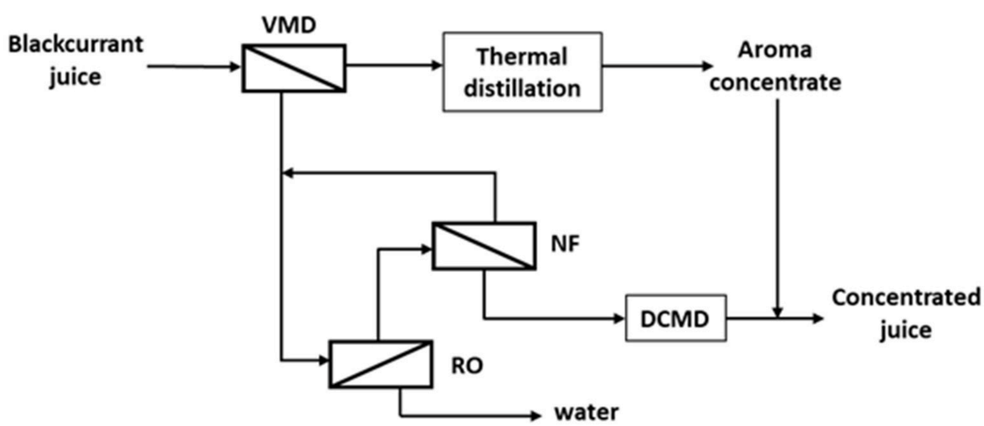

FIGURE 6 | Schematic process layout for concentration of blackcurrant juice based on membrane processes (VMD, vacuum membrane distillation; RO, reverse osmosis; NF, nanofiltration; DCMD, direct contact membrane distillation) adapted from Sotoft et al. (55, 56).

observed for other preservation techniques, differences in the resistance of microorganisms to HHP have also been reported: yeasts and molds are less resistant than vegetative bacteria cells; Gram+ bacteria are generally more resistant than Gram- bacteria; bacterial spores are highly resistant to HHP conditions.

Currently, HHP processing is a well-established non-thermal technology for increasing food safety and/or extending the shelf-life of refrigerated foods of high value (61). Products pasteurized by HHP processing show nutritional and organoleptic properties similar to those of the raw/fresh products, which is contrary to conventional thermal treatments (62, 63). Comparative studies on non-thermal preservation techniques reported that the effects of HHP on microbiological quality and physicochemical properties of juices were higher, or similar to, those observed with other non-thermal techniques, such as PEF (62). However, contrary to PEF, HHP processing is increasingly used at commercial, industrial scale for specific market niches, such as vegetable products (∼33%), meat products (∼30%), juices and beverages (∼12%), seafood, and fish (∼15%) (13, 16, 61). In 2011, there were 125 HPP units installed in over 60 companies, producing 250 different HHP-treated products. An HHP industrial unit (600 MPa, room temperature, overall production around 5,000 kg/h) is almost as expensive as a PEF industrial unit, and costs between 0.77 and 3.15 million US $, depending on the vessel volume (55–420 L). Currently, the main suppliers of HHP installations are Avure technologies (USA), Hiperbaric (Spain), HPBioTech (France), Multivac (Germany), ThyssenKrupp (Germany), and Steribar HPP (Hydrolock, France). In terms of production costs, high-pressure processing requires power to increase pressure. Due the adiabatic heat of compression, the theorical total energy input for processing pure water at 600 MPa is about 122 kJ/kg. The cost of HHP will also depend on the total cycle time (i.e., pressure increase, holding, and loading/unloading times), vessel filling ratio, energy, labor, and capital costs (61). Recently, Sampedro et al. estimated that the total cost of orange juice pasteurization using HHP (0.107 $/L) was 7-fold higher than that of conventional thermal processing (0.015 $/L), and 3-fold higher than that of PEF treatment (0.037 $/L) (64). They also estimated that non-thermal processing technologies may have higher environmental impacts (in terms of CO_2 production) than traditional thermal pasteurization. Aganovic et al. discussed similar trends for the pasteurization of tomato or watermelon juice (65). They calculated that the specific energy uptake was about 0.20, 0.12, or 0.04 kWh/L of juice by using HHP, PEF, or thermal treatment, respectively. From the environmental (Life Cycle Assessment) perspective, no great differences in environmental impacts have been observed over the three investigated technologies with "gate to gate" system boundaries. A slightly higher impact was observed for HPP, followed by PEF and thermal treatments. Even though the differences of processing stage were assigned to the use of energy, the largest environmental impact was associated with 250 ml PET bottles production (∼85%) (65).

Finally, it is noteworthy that inactivation of bacterial spores can be obtained with HHP by following different strategies of which: (1) full inactivation in one step by severe temperature or pressure-temperature combinations (up to 800 MPa and 75°C), or (2) germinating spores by temperature and/or pressure (50–300 MPa) and then inactivating them in a subsequent temperature or pressure/temperature treatment (>400 MPa) (16, 19). From an energetic point of view, combining thermal and high-pressure sterilization allows for an overall reduction of energy input of 20%, as compared to thermal sterilization alone, due to the recovery of adiabatic heat of compression (15).

High Pressure Homogenisation

High pressure homogenisation (HPH) was initially dedicated to cell disruption and removal of intracellular compounds from microorganisms (66). A growing interest for over 15 years was focused on the mild non-thermal stabilization of food; UHPH has been evaluated as an alternative to conventional heat treatments of liquid foods to inactivate microorganisms and endogenous enzymes, and consequently increase the shelf life of products (20, 21, 67, 68). The efficiency of UHPH for microbial inactivation of spoilage microorganisms and foodborne pathogens has been demonstrated to increase with the pressure level, the extent of recycling through the homogenizer, the temperature of the processed fluid, but depends on the characteristics of the food matrix (e.g., water and fat contents, viscosity, pH, etc.) and also the type of microorganisms present.

Several studies have demonstrated that HPH is equivalent to food pasteurization. HP technology developments have been many, especially concerning HP intensifiers, materials resistant to HP, and also sophisticated homogenization valves with seats and needles built in ceramic or coated with artificial diamond have allowed for increases in nominal pressure levels up to 350–400 MPa (20), and thus the application of UHPH for bacterial spore inactivation (68–70). However, UHPH has to be combined with high inlet temperatures for liquid foods to obtain a treatment equivalent to thermal sterilization (71, 72). At the present time, the vast majority of studies have focused on the quantification of the UHPH inactivation efficiency, and on understanding of the impacts of the various phenomena involved in this process on the inactivation of microorganisms or enzymes. Even though it has been determined that this process can pasteurized liquid foods while preserving sensorial and nutritional qualities, and can limit the use of high temperatures, very few studies have examined or evaluated the sustainability aspects of UHPH processing (21, 73). UHPH was recently compared to classical thermal processing by Valsasina et al. milk production (22). They compared the environmental impacts of UHPH technology to those of a conventional thermal treatment (UHTH—ultra-high temperature treatment and homogenization) using life cycle assessment (LCA). At a pilot scale, a lower energy consumption was determined for UHPH compared to UHTH, with consequently a significantly lower carbon footprint for UHPH. Electricity production was evaluated as the main input in the LCA for UHPH and UHTH. By introducing energy recovery in the UHPH equipment, a significant improvement of the LCA score for UHPH could be obtained. UHPH being available currently only at a pilot scale, the evaluation of LCA at industrial scale has to be carried out by upscaling approaches (22). The main drawback concerning the potential of UHPH to stabilize liquid foods at industrial scales concerns equipment development (e.g., pumping, intensifiers, and valves) that must ensure the flow capacity of production lines. This is a challenge for the equipment manufacturers. Currently, piston-gap homogenizers are proposed by Avestin (Canada), APV (UK), Bee International (USA), GEA Niro Soavi (Italy), Stansted Fluid Power (UK), and Ypsicon (Spain) and another system called microfluidizer is marketed by Microfluidics (USA).

Carbon Dioxide Processes

CO_2 processes have been investigated for their ability to stabilize products according to several criteria: bacterial content (26), undesired enzymatic activity (39), texture (31), or nutritional quality (27, 35, 39). To our knowledge, no experimental data have been published on the cost of processes using CO_2 for these purposes (26). Nonetheless, the treatment intensity in terms of pressure/temperature can be discussed and compared with currently used technologies. Under pressure, CO_2 dissolves in aqueous media by forming carbonic acid, which lowers the pH (74). For pH-sensitive proteins, mild treatments involving pressures between 0.1 and 7 MPa and temperatures between 4 and 45°C for <1 h can be sufficient to inactivate polyphenol oxidase in various food products (74), form stable gels with silk proteins (30), and stabilize curcumin in casein micelles (27). These mild process parameters can be considered eco-efficient compared to conventional treatments (temperatures above 55°C or addition of chemicals) required to obtain equivalent protein modifications (30, 74). The inactivation of vegetative microorganisms by CO_2 requires stronger conditions, and has been demonstrated to be the consequence of simultaneous effects: lowering of pH and CO_2 bubble formation when pressure is released can induce chemical alterations of structural proteins and enzymes, as well as mechanical disruption of cell membranes, respectively (26, 74). Inactivation of vegetative microorganisms by CO_2 (sometimes called CO_2 pasteurization) has been intensively studied for temperatures ranging between 20 and 50°C and pressures ranging between 4 and 60 MPa; this technique represents another alternative to thermal pasteurization (which is most often over 80°C) and to high pressure inactivation (over 150 MPa) (26, 74). Effective inactivation of more than 3 Log_{10} reductions for various microorganisms have been obtained after a few minutes to <1 h of treatment (**Table 1**). For products with substantial protein content, like milk or peach juice, undesirable texture modifications have been reported due to protein aggregation (32, 75). However, for many products with low suspended protein content, e.g., apple and grapefruit juice, beer, sake, or solid fresh-cut vegetables, CO_2 pasteurization appears to result in better quality (texture, color, flavour, and nutritional properties) than equivalent thermally treated products (26, 32, 35, 39). Several patented systems exist, and industrial equipment have already been available for more than a decade from manufacturers like Praxair or GEA groups, but industrial applications are still in development. In fact, as reported by Spilimbergo et al. the main drawback remains the equipment cost compared (for example) to heat exchangers. In their paper, they briefly present an estimation of the cost of pasteurization of apple juice by CO_2 treatment as compared to the thermal pasteurization using tubular heat exchangers. They claim a treatment cost of only a few cents per liter higher for CO_2 treatment compared to thermal treatment, and they highlighted that larger scale units can be economically feasible (26). Based on current scientific knowledge, there are only few patents available, and no currently used equipment include a CO_2 recycling unit. Finally, CO_2 sterilization, i.e., the inactivation of endospores, has been less documented than inactivation vegetative microorganisms. It has been reported that effective CO_2 treatment involves temperatures above 85°C (40, 41) which necessarily consumes more energy than the CO_2 pasteurization unit. Rao et al. (40) indicated that the pressure level (below 30 MPa) has fewer effects than increasing temperature, but the fact is that supercritical CO_2 allows for endospore inactivation at temperatures for which temperature alone has no effect. In fact, endospores are known to be extremely resistant organisms which required temperatures above 120°C in food processes to be inactivated (76). Therefore, CO_2 sterilization can be a promising process, but require further investigations.

Pulsed Electric Fields

The potentialities of PEF as an alternative technique to thermal pasteurization has been widely investigated in the last six decades. A large number of studies have shown the efficacy of PEF treatment for the inactivation of most spoilage and pathogenic microorganisms. The main factors governing microbial inactivation by PEF are the treatment parameters (i.e., electric field strength, total treatment time, energy density input, pulse width and shape, and pulse repeat frequency), the microbial characteristics, and the product parameters (electrical conductivity and pH) (48, 77). Even though exact correlations between process parameters and microbial inactivation are not yet fully elucidated, it has been extensively demonstrated that (1) increasing the electric field strength and/or the total treatment time increased microbial inactivation; (2) the electric field strength applied must exceed a critical value that ranges from 5 to 15 kV/cm, depending upon the microorganism or treatment chamber. Differences in the resistance of microorganisms to PEF have been widely reported: vegetative bacterial cells are more resistant than yeasts or molds; Gram+ bacteria are generally more resistant than Gram- due to the differences in cell wall membranes; and bacterial spores generally resist electric pulse conditions which inactivate vegetative cells (48, 77). The potential of PEF to achieve sufficient reduction for most of the spoilage and pathogenic microorganisms has been proven in a broad variety of liquid foods, including fruit and vegetable juices, model beer, milk, and liquid egg (52, 62). Even if there are still conflicting views about the inactivation of enzymes by PEF, data available show clearly that plant enzymes are much more resistant to PEF than vegetative microbial cells (78). PEF treatments have been reported to induce inactivation of enzymes involved in plant spoilage such has pectin methyl esterase, and peroxidase as PME (up to 97%), polygalacturonase (up to 76.5%), polyphenol oxidase (up to 97%), peroxidase (up to 97%), and lipoxygenase (up to 64%). However, to reach these levels of enzyme inactivation large specific energies (1,066–44,000 kJ/L) are required, while only 50–1,000 kJ/kg are sufficient for microbial inactivation (78). More recently, numerous studies have reported that PEF-pasteurization of plant-based beverages at mild temperatures can minimize changes in their physicochemical characteristics (e.g., pH, color, aroma, and flavor) and can significantly improve the nutritional properties of beverages due to retention of higher amounts of health-related biomolecules (e.g., vitamins, polyphenols, carotenoids...), as compared to thermal processing (52, 79–81). Despite the large quantity of scientific data available in the literature about the benefits of PEF processing and various technology transfer projects, there is still very little industrial implementation of PEF for pasteurization of liquids, and it is primarily limited to waste water treatment (82).

PEF treatment is usually considered to have a high initial investment costs and elevated processing costs, with higher energy input than a thermal process with heat recovery capacity (83–85). For applications requiring high electric field strength and/or high energy input (20–40 kV/cm, 100–1,000 kJ/kg), the investment costs is estimated to be in the range of 2–3 million US $ for an industrial scale device of 5 t/h (15). Recently, Sampedro et al. estimated that the total cost of orange juice pasteurization using PEF was about 0.037$/L of juice, against 0.015 $/L for thermal pasteurization, of which capital costs accounted for 54% while utility charges (mainly electricity) accounted for 11% (85). Aganovic et al. calculated that the specific energy uptake to pasteurize tomato or watermelon juice was about 0.12 or 0.04 kWh/L of juice by using PEF or thermal treatment, respectively (65). From an energetic point of view, improvement of PEF processing (higher microbial and enzyme inactivation with lower field strength and less electrical energy) can be achieved by combining PEF with other treatments (such as pH, antimicrobials or heat) (11, 62). In particular, using elevated inlet temperatures (up to 55°C) allows the reduction of energy input to achieve the same inactivation level, and the need to preheat the product provides a potential to recover the electrical energy dissipated into the product (15). However, it would be important to optimize the process conditions while still maintaining the potential quality benefit of PEF (62, 65). In the last few decades, the application of PEF has also been studied as pre-treatment for other food preservation techniques. The main studies dealing with PEF-assisted drying or freezing have recently been reviewed by Barba et al. (52) and Chemat et al. (11).

Membrane Processes

Initiated in the early 1960s, the industrial interest in membranes firstly focused on water desalination. But membranes were rapidly introduced in food processing since they permit the replacement of conventional thermal technologies or reduce their negative impact during stabilization processes. For instance, microfiltration (MF) is currently widely used for cold stabilization of milk prior to transformation into cheese or to extend its shelf life without applying a time-temperature treatment. More than 99% of the bacterial are removed without thermal degradation of protein or off-flavor development. Concentration, polarization, and membrane fouling—the main drawbacks of membrane filtration, can be limited by applying a uniform transmembrane pressure (TMP) all along the membrane via the circulation of the permeate co-current with the retentate (for example, Bactocatch system®, AlphaLaval; Invesys® APV). It is also possible to use ceramic membranes with a linear hydraulic resistance gradient (e.g., GP Membralox® membrane Pall-Exekia; Isoflux® membranes Tami-Industries) (86). Another important application of membrane technologies in dairy processing is the MMV procedure, patented by Maubois Mocquot and Vassal in 1969, in order to pre-concentrate milk by ultrafiltration (UF) before cheese making (87). The MMV process offers many advantages (i.e., higher overall cheese yield compared to traditional processing, conversion of cheese production to a continuous operation, and elimination of the need for large storage tanks) leading to high operational efficiency with lower overall capital costs (88).

The first applications of membranes in the dairy industry were mainly driven by product innovation. However, the combination of membrane technologies with classical thermal operations or with other emerging technologies can significantly reduce the energy consumption during milk powder production, which is responsible for about 15% of the total energy used in the dairy industry. Indeed, huge amounts of energy are required for evaporation and spray drying steps. Preconcentrating the milk by reverse osmosis (RO) before thermal evaporation is advantageous because the low energy consumption compared to evaporation (14–36 kJ/kg water removed, and 300 kJ/kg water removed, respectively) (89). Nevertheless, according to Moejes and van Boxtel, the best option would be to replace heat evaporation by a combination of a radio frequency heating system which generates heat directly within the product by using electromagnetic waves combined with membrane distillation (MD), which is a membrane contactor process (89).

In contrast to reverse osmosis, which is a pressure-gradient process involving a dense membrane, membrane distillation involves a porous hydrophobic membrane in order to create an interface for mass transfer between the solution to be concentrated (feed) and the stripping solution (water at low temperature) (i.e., permeate). The hydrophobic nature of the membrane prevents the penetration of the liquid phase and creates a liquid-vapor interface at the entrance of each pore. Due to the temperature gradient, evaporation occurs at the feed side; then the volatile compounds (mainly water in the case of milk concentration) diffuse across the membrane and are condensed into a liquid phase (Direct Contact Membrane Distillation (DCMD) or over a cool surface (Air Gap Membrane Distillation (AGMD) or are removed by a gas flow [Vacuum Membrane Distillation (VMD) and Sweep Gas Membrane Distillation (SGMD)] (90). In contrast to reverse osmosis, MD presents a low flux sensitivity toward concentration of the processed fluid and thus permits a high concentration level. Nevertheless, the implementation of MD for milk production requires further investigation since the process efficiency is still limited by membrane fouling (55).

Membranes technologies also present high potentialities in beverage processing (91). MF and UF can advantageously replace conventional filtration processes for clarification and microbial stabilization of juice (i.e., high product qualities, continuous processing, low waste, etc.); juice concentration can be carried out by RO up to a limited concentration rate (up to 30% TSS (total soluble solute), but higher TSS (up to 60%) can be achieved by osmotic membrane distillation (OD). In this process a porous hydrophobic membrane is used to separate juice from a stripping solution with a low water activity (i.e., a brine). On the contrary to MD, the driving force is no longer the temperature gradient, but the water vapor pressure gradient induced by the difference in the water activity of the aqueous solutions which flow along the membrane. Therefore, it is not necessary to heat the solution to be concentrated; its qualities are thus preserved. However, corrosion and high production costs due to the use of concentrated brine can be challenges to using OD. To avoid these drawbacks, Sotoft et al. proposed an alternative process for blackcurrant juice concentration (56). This new process combines different membrane techniques, allowing the production of aroma concentrate and concentrated juice. Firstly, the filtered blackcurrant juice is treated by VMD. The permeate, which contains aroma, is further concentrated by distillation while the retentate is then concentrated by a combination of membrane processes (RO, NF, and DMC). Finally, aroma extract is added to the concentrate (**Figure 6**).

ECO-FRIENDLY EXTRACTION AND VALORIZATION OF BIORESOURCES

Valorization of bioresources mainly consists in recovering high-value compounds from raw materials, by-products, or food wastewater. Extraction of intracellular molecules often involve cell damage techniques, such as fine mechanical fragmentation, thermal, chemical, and enzymatic treatments. These conventional techniques often require a significant amount of mechanical or thermal energy, long time steps, use of toxic solvents, or high temperatures that can degrade thermolabile compounds, and lead to a non-selective extraction. In the last few decades, emerging non-thermal technologies developed for food stabilization have also shown promising capabilities to be useful tools for more efficient and sustainable extraction/separation processes.

Hydrostatic High Pressure

HHP can damage cell membranes and then increase their permeability and enhance mass transfer rates of intracellular molecules (15, 19). However, HP-assisted extraction is a quite recent application of HHP processing. High hydrostatic pressure (HHP) treatment (200–700 MPa, moderate temperature) has been successfully implemented to extract bioactive compounds (phenolic compounds, carotenoids, glucosinolates…) from natural sources (grape, *Maclura pomifera* fruits, berries, tea leaves…) or by-products (grape, tomato, and citrus) (17, 52, 92–94). Diffusion of bioactive compounds could be done under pressure in water mixed or not mixed with other solvents, and effectiveness depends on pressure level, pressure holding time, liquid/solid ratio, type of solvent, and solvent concentration (17).

Overall, as compared to conventional solvent-extraction, HP-assisted extraction allows higher extraction yields to be obtained, with a shorter process time and a reduction of the use of toxic solvents. Even though only lab-scale studies have been performed on this topic until now, and without energetic and economical estimations, HP-assisted extraction represents a promising technique to improve process efficiency and thus sustainability.

High Pressure Homogenization

A peculiar interest of dynamic high pressure concerns the eco-extraction of valuable bioactives from different types of biomass, such as algae or microbial organisms (95–97) but also from by-products or co-products to up-cycle them (98, 99). High pressure homogenisation (HPH) is mainly appropriate for these applications since the pressure level applied is more often up to 150 MPa, and there is a link between the particle gap width of HPH equipment and the particle size. The bioactives extracted are particularly prized for their biological activity such antimicrobial or antioxidant activity, but also for their nutritional properties. As with mechanical technology, HPH is used to carry out a physical disruption of organism cell membranes or to reduce particle size. In the first case, the disruption of cell membranes due to the combination of turbulence, recirculation and cavitation phenomena but also impingements on the chamber allows the non-selective release of the intracellular fluid and also cellular organelles (66). In the second type of application, also called nanosizing, HPH is applied to reduce the size particle and so to increase the exchange surface and consequently the particle activity. The efficiency of HPH technology to disrupt membrane cell is influenced positively by processing parameters: the pressure level and the number of passes (95), but strongly depends on the macrostructure of the cell wall (97). From a sustainability point of view, HPH allows the extraction of intracellular valuable components without the addition of solvents or chemicals, limiting waste to be reprocessed. By nanosizing of bioactive plant material, High pressure homogenisation (HPH) could be an alternative, less time-consuming and lower cost compared to the conventional protocol requiring extraction, fractionation and isolation (99).

Concerning bio-refinery applications, microalgae is a fast growing sector, and has a significant activity in developing operation units less costly in the downstream process where the key step is the cell disruption consisting in breaking or weakening the cell wall integrity. Early studies were carried out at low concentrated algal dispersions (<5%, w/w DB) and have concluded that HPH energy consumption was significantly higher than the potential energy output of algal-derived biodiesel (100). Yap et al. investigated the influence of the feed concentration on the HPH capacity, power draw and cell disruption efficiency for *Nannochloropsis sp.* suspensions (0.1–25%, w/w DB) (101). HPH efficiency was independent of homogenizer feed concentration and solely dependent on the pressure level. Besides, HPH could represent between only 6% the energy content of the resulting biodiesel (conditions: (60 MPa, 25% solids, 30% TAG). Concerning the energy consumption, Safi et al. quantified the specific energy input based on the inlet pressure, the number of passes and the pump efficiency expressed per unit of treated biomass for the disruption of *Nannochloropsis gaditana*, which is microalgae characterized by a rigid cell wall, treated at a high concentration (100 g/L) (102). Additionally, the energy input was correlated to the protein yield. HPH was concurrently compared to PEF, bead milling and enzymatic treatment. HPH resulted in the lowest specific energy input related to the obtained protein yield and an energy cost per unit of released protein evaluated was between 0.15 and 0.25 *e*/kg (compared to 2–20 *e*/kg in case of PEF).

A specific drawback has to be highlighted: HPH induces total cell disruption and is consequently characterized by a poor selectivity, so downstream processing is required to achieve high purity for a specific target compound.

Carbon Dioxide Processes

The use of pressured CO_2 to separate and extract proteins has been investigated for various substrates like collagen/gelatin from sponge or soy flour soluble fraction at alkaline pH (28, 29). As previously described, this method is based on the control of the aqueous media pH decrease to solubilise or to aggregate protein. The precise pH control by the pressure applied allows for efficient recovery and sequential separation. The conditions required are quite low, with a pressure up to 3 MPa and 25°C. This process clearly represents an eco-efficient alternative to an equivalent chemical acidification method to separate and extract protein fractions. Nonetheless, no data on the economical aspect has been published yet.

The most common food processes using CO_2 is supercritical CO_2 extraction. Since the first industrial implementation in the 1970's with coffee decaffeination, this process has been progressively investigated and industrially implemented for a wide variety of food products, including solid vegetable and aqueous or oily liquid. In fact, CO_2 has moderate critical conditions ($T = 31°C/P = 7.38$ MPa) and has been developed as an alternative to the energy costly and pollutant reference methods using organic/organochlorine solvents and distillation (103). SC-CO_2 extraction typically operates for pressure ranging from 8 to 50 MPa and temperature between 40 and 80°C (**Figure 1**). The highest operating pressure/temperature conditions are used for lipid and other non-polar high molecular weight compounds, with $P > 28$ MPa and $T > 60°C$, whereas moderate temperature, or both temperature and pressure conditions are frequently used for other compounds like aromatic compounds, ethanol, polyphenol, and hydrophobic vitamins (11, 23, 104).

However, SC-CO_2 extraction is not so common in industrial applications (<40 industrial facilities have implemented in Europe in 2003), and there are still few detailed papers dealing with economic aspects (26, 105). According to Perrut (2000), the equipment cost is relatively high and increases linearly with its size. However, SC-CO_2 extraction has a moderate exploitation cost, so finally the production cost per kilogram of fed matter can be very competitive with the conventional processes, with several advantages in term of green label (105, 106).

Several studies have investigated the potential of SC-CO_2 extraction to reduce waste by valuing co-products, such as oil recovery from palm kernel (46) or lipid and terpenics high value compounds from bagasse left after latex extraction (43), but related economic aspects are insufficiently documented. Otherwise, recent papers have investigated the possibility to increase the number of compounds that could be recovered (including more polar compounds like fatty acid, phospholipids, certain carotenoids…) by using co-solvent extraction using 5–50% ethanol for process fluid (11, 42, 104). Most often these works have shown higher recovery yield and faster extraction for pressure and temperature closest to the critical point than for SC-CO_2 alone. Even more recently, carbon dioxide expanded solvent extraction techniques (i.e., the process fluid used is a mixture organic solvent and CO_2) have been developed and seem even more efficient than co-solvent extraction for the same operating conditions (11, 104, 107).

Pulsed Electric Fields

Based on its capacity to permeabilize plant cells at moderate electric fields (0.7–3.0 kV/cm), the application of PEF has been investigated as a pretreatment to improve mass transfer of water or intracellular compounds from vegetable tissues or bio-suspension cells. A large number of studies have been devoted to this issue and showed that PEF-pretreatment represents a promising green alternative method for different applications, such as diffusion extraction, osmotic treatment, pressing extraction, drying and freezing. Besides increasing the mass transfer, PEF-assisted processing showed other advantages as compared to conventional ones, with improvement of extraction yields, decrease of processing time, decrease of process intensity (temperature, solvent…), and reduction of heat-sensitive compounds degradation (11, 52, 108, 109). The important features of moderate PEF treatment, as compared to other green alternative methods, are the possibility of pore resealing after treatment and the formation of different pore sizes in electroporated cell membrane depending on PEF conditions. Therefore, intracellular compounds of different molecular size may be selectively recovered and more easily purified under the PEF treatment (110). PEF-assisted extraction has been particularly investigated for extraction by diffusion of colorants (chorophylls, carotenoids, betalains…), sucrose, polyphenols, polysaccharides, proteins, and others secondary metabolites from vegetal, roots, mushrooms, microalgae or seaweeds and for pressing extraction of fruits juices (apples, grapes…) or oils (olive, rapeseed) (79, 96, 109, 111–114). The quality of products (purity, color, texture, flavor, and nutrient) extracted from solid foods (sugar beets, apples, grapes…) and quality of proteins and polysaccharides extracted are less degraded by PEF than by conventional mechanical or chemical pretreatment (108, 110). More recently, several studies pointed to the potentialities of PEF processing for valorization of waste and by-products from agricultural and food processing and for development of sustainable biorefineries (17, 115). Particularly, PEF pretreatment was shown to be more efficient than conventional techniques to extract high-value compounds (phenolics compounds, anthocyanins, carotenoids, pectins, essential oils…) from by-products of artichoke, blueberry, grape, flaxseed hulls, citrus, Norway spruce, alfalfa, rapeseed stem (52, 113, 115–117)…. In many cases, PEF treatment even in combination of mechanical or solvent processing, represents a "greener" extraction processing, compared to conventional techniques, due to higher extraction yield, lower energy consumption and reduced utilization of toxic solvents.

From an energetic point of view, the energy consumption for production of damaged plant tissues varied from 2 to 4 kJ/kg for red beetroot or sugar beet, 6 kJ/kg for sugar beet or around 16 kJ/kg for potato (52), that is significantly lower than conventional methods, such as mechanical processing (20–40 kJ/kg), enzymes (60–100 kJ/kg) or heat treatment (>100 kJ/kg) (15). However, for hard or resistant materials (lignocellulosic biomass) higher electric fields (up to 20 kV/cm) and energies (up to 800 kJ/kg) are required as compared to soft tissues. For juice and oil extraction, in addition to lower energy requirements for tissue disintegration, PEF application provides a possibility to reduce energy required for fruit juice pressing (15). The economic cost for PEF treatment necessary to recover valuable compounds from different matrices (0.1–0.5 euros/ton for chicory, grape skin, fennel, red beetroot, soybean or sugar beet) was estimated to be significantly lower as compared to enzymatic one (7.5 euros/ton) (116). In the same way, Toepl and Heinz (2011) estimated that the total cost (considering the electricity cost, equipment investment, maintenance cost, labor rent, water…) for apple pulp PEF processing was around 2.69 euros/ton as compared to 8.50 euros/ton for enzymatic maceration (118). This way, PEF represents an economically profitable and sustainable alternative and allow the production of juices and extracts presenting higher quality attributes.

From an engineering point of view, large scale biomass PEF-processing devices (up to 50 t/h) have been develop for industrial applications. For example, an industrial system to enhance yield of cloudy apple juice is operated in a German fruit juice company at a 10 t/h scale. PEF pretreatment of potatoes to improve cutting is currently used in 40 French fries companies (115). Currently, the main suppliers of PEF installations for pasteurization or extraction applications are PurePulse (Netherlands) Pulsemaster (Germany), DTI/Elea (Germany), Scandinova (Sweden), Steribeam (Wek-Tec, Germany).

Membrane Processes

Strictly speaking, single membrane operation cannot be considered as an extraction process. However, combinations of different membrane processes or integration of a membrane operation in an existing industrial process helps to achieve the recovery of valuable compounds from food waste or raw materials. The main successful applications of membrane processes which allow for an increase in the sustainability and the profitability by a more rational utilization of the raw material are undoubtedly in the dairy industry for the production of partially demineralized whey on the one hand, and the production of lactose on the other hand.

Whey is actually the main by-product of dairy industries; it can be obtained during the traditional cheese making processes or as a result of the implementation of ultrafiltration for the treatment of milk to produce cheese or to perform milk standardization (UF whey permeate) as well as for its use to prepare whey protein concentrates (WPC) and whey protein isolates (WPI) (119). Whey obtained during cheese making processes are generally used to produce whey powder. According to cheese making processes, some wheys can contain high amounts of salt which can alter nutritional and food functional characteristics of the powder. Consequently, the value of whey powders increases when salt concentration is reduced and especially when monovalent cations are removed before drying. In contrast to chromatography generally used for demineralization, NF appears to be a more suitable process to achieve this objective since it ensures a simultaneous pre-concentration and partial demineralization of the product. Indeed, NF membranes are able to retain the valuable compounds of whey, such as protein and lactose as well as multivalent ions (i.e., calcium) while monovalent ions are removed in the permeate. Román et al. reported that the efficiency of the process increases when NF is operated in diafiltration mode (120). Depending on their protein contents UF whey permeates can be uses to prepare WPC and WPI. These processes involve at least one or more UF steps which produce permeate with high lactose content (121). The recovery of this lactose is possible thanks to a NF step (122). According to da Siva et al., who studied different combinations of integrated production of whey protein concentrate and lactose derivatives the recovery of lactose increases considerably the economical attractiveness of plants producing WPCs (123).

Although the labeled products derived from food waste are still rather limited and concern mainly dairy by-products (i.e., WPI, lactose), numerous studies have reported the potentialities of membrane processes for the recovery and reuse of food by-products. The combination of UF and NF steps appears to be an efficient purification and concentration process for recovering bioactive peptides from fish protein hydrolysates (124, 125). The separation efficiency of the isolation of charged compounds from hydrolysates containing other neutral solute of similar size can even be further improved by coupling NF and electrodialysis with ultrafiltration membrane (EDUF) (electrically-driven process) in a same process line thanks to the synergy of both driving force (pressure and electrical potential) (126). More recently, there is a growing interest for the production of purified extracts of phenolic compounds involving membrane technologies and in particular NF (127–129). Basically, after the extraction step a two-step membrane separation process has been used, starting with ultrafiltration to remove larger molecules (proteins, polysaccharides and other impurities) followed by nanofiltration for further purification (elimination of salts) and concentration. Sometimes, a microfiltration step is carried out prior to UF step and the NF step is replaced or completed by a reverse osmosis step. However, despite the proven qualities of extracts obtained, investigations are needed in order to guarantee the success of these processes at the industrial level, particularly regarding their performances limited by solute-membrane interactions (130). Further research should focus on the development of membrane materials as well as on process design to obtain high transfer rates and higher selectivity.

WATER RECOVERY AND FOOD WASTE MANAGEMENT

Beside improvement of processing efficiency by significant decreases of energy consumption, process intensification also aims to reduce waste generation and promote a more rational use of natural resources, in particularly water. Indeed, many countries (i.e., China, India, Middle East countries, etc.) have to face to water scarcity which renders the re-use or recycling of water essential for economic and environmental reasons (131). Food industry is one of the most water-consuming industries; it requires large amount of high-quality water for food manufacturing but also water for cleaning purposes, transportation or heat-exchanges. In addition, food processing generates high volume of pollutant wastewaters. These wastewaters are generally non-toxic but their characteristics (chemical oxygen demand COD, minerals, suspended solids, etc.) vary with their origin (type of food industry) and their usage. Even if the re-use of water at the food processing stage is difficult to envisage for sanitary reasons, Beneduce et al. demonstrated that it could be used for irrigation of agricultural crops without significant increase of potential health risk related to microbial quality (132). Moreover, recycling and/or reconditioning water offer the possibility to decrease of environment and water footprints of food processing industry by saving up to 60% of the total water usage (131).

The use of non-thermal technologies discussed above, and in particular membrane separation processes, can help to achieve this goal since they permit the concentration of waste organic matter. Introduced 30 years ago in water treatment processes, membranes separation processes are currently widely implemented as secondary treatment (namely membrane biological reactor (MBRs) which combines biological reactors with membrane filtration units) and tertiary advanced treatments (mainly NF or RO operations) for urban wastewater (133), as well as for decontamination of agro-food industries wastewaters (134, 135). More recently, the co-management of domestic wastewater and food waste in an anaerobic membrane bioreactor (AnBMR) appears to be a potentially attractive strategy since it permits high COD removal and a net positive energy balance of the process due to a simultaneous methane production (136, 137).

In addition, pressure driven membrane processes including MF, UF and NF were successfully used to recover the functional characteristics of soda cleaning in place (CIP) solutions which can thus be re-used (138, 139). Salehi et al. reported that NF permits the reconditioning of colored brines used for ion-exchange regeneration in the sugar industry (140).

The major drawback of membranes processes, irrespective to the technology considered, is membrane fouling which reduces the permeation flux and thus increases the operational cost. This problem has been widely investigated for years, and among the studied strategies, PEF has also been tested for control of biofouling, disinfection of domestic or waste waters (141, 142), or for the pre-treatment of sludges produced during wastewater treatment (15, 143–145). In this last application, it has been shown that PEF facilitates the disintegration of microorganisms and consequently improves the bio-availability of organic carbon, biogas production, solids removal, and sludge quality after anaerobic digestion. For example, a sludge reduction of 27–45% was achieved after implementing electrical treatment to the return activated sludge at 1,650 kJ/kg TSS (146). However, since PEF treatment in wastewater treatment has only been applied at lab or pilot-scale, the energy efficiency of this non-thermal technique can only be estimated, and should be optimized technologically and economically for further industrial implementation.

CONCLUSION

High hydrostatic pressure (HHP), dynamic high pressure (high pressure of homogenization, HPH, and ultra-high pressure of homogenization, UHPH), carbon dioxide treatment, PEF, and membrane processes are non-thermal technologies. For decades, they have been investigated for food applications for the purpose of food product stabilization and extraction, as alternative processes to conventional application of thermal treatment, and/or the use of non-eco-friendly solvents. All of them allow for minimal-processed food with improved quality attributes compared to their thermal counterparts. In the same way, membranes and PEF already have a long research story for the treatment of industrial wastewaters, allowing for significant recoveries and thus wastage reduction. Therefore, these technologies are considered promising for the present and future development of sustainable food applications. However, the progress made on the research and the results obtained for their industrial implementation differ from one technology to another, making a direct comparison of these processes difficult. Most of these non-thermal processes are currently applied at a lab or pilot scale, thus inducing higher production cost than large scale industrial thermal devices. Furthermore, recent studies have pointed out the need to consider the overall environmental, economic and social impacts (i.e., energy balances, LCA, waste production/reduction, cost of production, quality of improving standards of living…) of the implementation of these "novel" technologies throughout the food chain. Thus, further cross-sectional investigations should be done to really determine the potentialities and limits of non-thermal technologies to improve the sustainability of food processing operations, and to identify for each "novel" technology, the steps to be optimized to make them more sustainable.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The main editorial contributions of each author are LP-P: high hydrostatic pressure and pulsed electric fields; DC-L: High pressure homogenisation; CC and SM: Carbon dioxide processes; M-PB: Membrane processes.

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Is Grassfed Meat and Dairy Better for Human and Environmental Health?

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The health of livestock, humans, and environments is tied to plant diversity—and associated phytochemical richness—across landscapes. Health is enhanced when livestock forage on phytochemically rich landscapes, is reduced when livestock forage on simple mixture or monoculture pastures or consume high-grain rations in feedlots, and is greatly reduced for people who eat highly processed diets. Circumstantial evidence supports the hypothesis that phytochemical richness of herbivore diets enhances biochemical richness of meat and dairy, which is linked with human and environmental health. Among many roles they play in health, phytochemicals in herbivore diets protect meat and dairy from protein oxidation and lipid peroxidation that cause low-grade systemic inflammation implicated in heart disease and cancer in humans. Yet, epidemiological and ecological studies critical of red meat consumption do not discriminate among meats from livestock fed high-grain rations as opposed to livestock foraging on landscapes of increasing phytochemical richness. The global shift away from phytochemically and biochemically rich wholesome foods to highly processed diets enabled 2.1 billion people to become overweight or obese and increased the incidence of type II diabetes, heart disease, and cancer. Unimpeded, these trends will add to a projected substantial increase in greenhouse gas emissions (GHGE) from producing food and clearing land by 2050. While agriculture contributes one quarter of GHGE, livestock can play a sizable role in climate mitigation. Of 80 ways to alleviate climate change, regenerative agriculture—managed grazing, silvopasture, tree intercropping, conservation agriculture, and farmland restoration—jointly rank number one as ways to sequester GHG. Mitigating the impacts of people in the Anthropocene can be enabled through diet to improve human and environmental health, but that will require profound changes in society. People will have to learn we are members of nature's communities. What we do to them, we do to ourselves. Only by nurturing them can we nurture ourselves.

Keywords: diet, nutrition, feedlots, grassfed beef, grazing, climate change, eat-lancet

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THE ROLE OF LIVESTOCK IN HUMAN AND ENVIRONMENTAL HEALTH

Palates link the health of soil and plants with animals and biophysical environments. A palate attuned to a landscape enables herbivores and humans to meet needs for nutrients and to self-medicate (1). That evolves from three interrelated processes: biochemically mediated flavor-feedback associations where cells and organ systems, including the microbiome, alter liking for wholesome foods as a function of needs; accessibility to phytochemically and biochemically rich foods; and learning *in utero* and early in life to eat wholesome combinations of foods (2). That occurs when wild or domestic herbivores forage on phytochemically rich landscapes, is reduced when livestock forage on simple mixture or monoculture pastures or consume high-grain rations in feedlots, and is greatly reduced for people who eat highly processed foods obtained in contemporary food outlets (**Figure 1**).

Diets affect human and environmental health. The global shift to highly processed diets has enabled 2.1 billion people to become overweight or obese and increased incidence of type II diabetes, heart disease, and cancer (3–6). These trends have been amplified by primary health strategies focused on treating symptoms rather than preventing disease by promoting healthy diets and lifestyles (7). Unimpeded, these trends will add substantially to a projected 80% increase by 2050 in greenhouse gas emissions (GHGE) from food production (8).

Industrial agriculture uses for crops or pastures nearly half of the ice-free land on Earth, contaminates fresh and marine waters with nutrients and biocides, and contributes roughly one-quarter of the total GHGE from all economic activities (9). The input is larger in developing countries where agriculture and related land use activities can be more than half of total emissions (10). Growing human populations and demand for meat are increasing GHGE by agricultural practices dependent on fossil fuels and by converting tropical forests, savannas, and grasslands to crop and pasture lands, threatening many plant and animal species with extinction (11–13).

Some contend grain-based livestock finishing systems have less environmental impacts than forage-based grazing systems (14). While ruminant livestock begin their lives on pastures, nursing from their mothers and eating forages, only 4% of young animals continue to forage on pastures while the other 96% go to feedlots in the U.S. (15). Feedlots are characterized by controlled production practices that combine genetics, animal husbandry, and "nutritionally optimized" feeds to yield fat animals in less time than with grazing systems. That combination accelerates growth and enables more meat to be produced per unit area of land. Thus, Poore and Nemecek (16) claim for key metrics, such as land use and GHGE, feedlot systems generate fewer negative environmental impacts per unit of meat produced, especially for beef. Compared with feedlots, some pasture-finished beef production systems have markedly lower climate impacts, but pasture systems that require significant synthetic fertilization, inputs from supplemental feed, or deforestation to create pasture have substantially greater climate impacts than feedlot systems (17).

Others contend regenerative agriculture can reduce GHGE and sequester GHG, with added benefits that include enhanced biodiversity and ecological function. That occurs as damage to soil—from tillage, inorganic fertilizers, and biocides—is rectified with plant cover and animal manure that continually nurture soil in ways not possible with conventional production of crops grown to feed livestock in feedlots (18–23). Plant diversity and grazing are vital for maintaining healthy soil to sustainably grow grains in rotation with pastures on farmland (22, 24). Integrating livestock and perennial plants with food crops can restore soil and ecosystem health and increase yields (25). Moreover, farmlands can be managed to enhance biodiversity from microbes in soil to plants, insects, fish, birds, and mammals including livestock that contribute to production of wholesome foods, healthy soils, clean water, and sequestering GHG (26).

Managed grazing is a vital part of regenerative agriculture. At the highest level of sophistication, a skilled shepherd is an "ecological doctor" who has learned to use grazing to produce meat or milk and to create environmental health (27, 28). The herd in his or her hands is a living organism, biological and ecological "tools" for creating health of soil, plants, wild and domestic animals, and humans. Managed grazing can moderate climate change, an outcome that challenges the view of feedlots as the best way to reduce GHGE from livestock (29, 30). Collectively, managed grazing and other regenerative agricultural practices—silvopasture, tree intercropping, conservation agriculture, and farmland restoration—rank number one as ways to sequester GHG (31).

As opposed to pastures with few plant species and feedlots, health is enhanced when animals graze phytochemically rich mixtures of grasses, forbs, shrubs, and trees (32–37). Diverse plant communities are nutrition centers and pharmacies that enable health prophylactically and therapeutically (1). They are thus etiologic in the health of herbivores, omnivores, and carnivores above and below ground. Animals foraging on phytochemically diverse pastures require less anthelmintics and antibiotics than animals foraging on monoculture pastures or in feedlots. Overuse of antibiotics in feedlots adds to antibiotic resistance, a global health challenge (38, 39).

Yet, during the past 70 years, people have confined livestock in feedlots under conditions that violate the five freedoms of animal welfare (40, 41). They are moved from familiar social and biophysical environments (home) to unfamiliar environments (feedlots), which violates their freedom from fear and distress. Animals in feedlots are fed total-mixed rations high in grain with little chance to self-select their own diets, which violates their freedom to maintain individual health and vigor and produces changes in blood cortisol and behavioral parameters indicative of stress (42, 43). Individuals vary markedly in their preferences for different foods due to past experiences and individuality in morphology and physiology, which differentially affects their abilities to tolerate excesses and deficits of nutrients in their diets (44, 45). Animals acquire aversions to foods eaten too often or in excessive amounts (46, 47), and large numbers of animals confined and fed only total-mixed rations high in grain experience stress and malaise (nausea) (48), which violates their freedom from discomfort. To deal with cumulative effects on

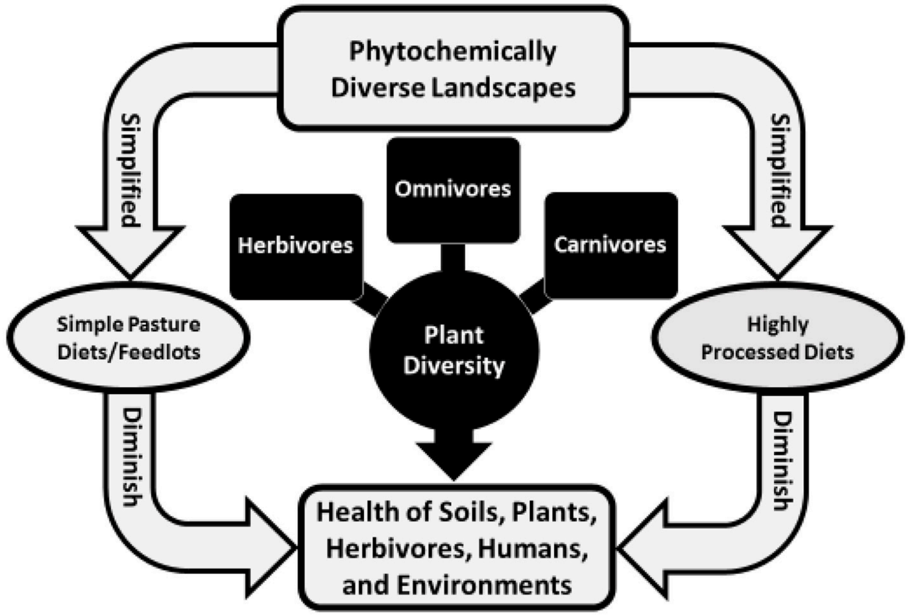

FIGURE 1 | The health of life in soils, plants, herbivores, humans, and environments (land, water, and air) is tied to plant diversity—phytochemical richness—across landscapes.

morbidity and mortality (49), animals are given antibiotics to counter illness from phytochemically impoverished diets and crowded conditions, which together violate their freedom from pain, injury, and disease.

Collectively, these practices, which have been scaled so people can afford to eat large amounts of grain-fed meat and dairy products, can be harmful for herbivores, humans, and environments (50–55). People in the U.S. eat meat and dairy at nearly three times the global average (56). Reducing intake of meat from feedlots, while increasing intake of meat from livestock finished on phytochemically rich landscapes, could reduce what some consider excessive intake of meat and increase intake of biochemically rich meat arguably of better quality, a key point not considered in the Eat-Lancet report (57).

While most livestock are fattened in feedlots in the U.S., and increasingly in other countries, those patterns are changing. In the U.S., for example, retail sales of pasture-finished beef have risen from $17 million in 2012 to $272 million in 2016 (15). That is 4% of beef sold and a market for pasture-finished beef that has grown at 100% annually for 4 years. People are also buying more dairy products produced from pasture (58). Interest in forage-fed meat and dairy is due to benefits for animal-welfare, consumer and environmental health, as well as authentication, terroir and geographical origin status.

Despite their alleged benefits, research has not elucidated linkages among plant diversity in herbivore diets and human health for either feedlot or pasture-based livestock production. Nor is plant diversity reflected in the generic label "grassfed," which is why the flavors and biochemical characteristics of "grassfed" beef differ (59–61). In the absence of studies, we review circumstantial evidence that grazing systems have unrecognized benefits for health by addressing four questions: (1) Are specific compounds (e.g., omega-3 fatty acids) etiologic in human health? (2) Does the phytochemical richness of herbivore diets influence the biochemical richness of meat and dairy, and if so, does that affect the flavor and satiating characteristics of meat and dairy? (3) Does biochemical richness of meat and dairy affect human health? (4) How do diets of herbivores and humans influence environmental health?

BIOCHEMICAL COMPLEXITY AND HUMAN HEALTH

Diet influences fatty acid profiles of animal tissues, and people often promote the health benefits of grassfed meat and dairy products based on improved ratios of omega-6 to omega-3 fatty acids (62, 63). Compared with diets high in cereal grains fed in intensive feeding systems, herbivore diets that are high in plants yield animal products that have higher levels of omega-3 fatty acids. Some scientists, medical doctors, nutritionists, and fitness advocates believe a healthy diet should have no more than 1–4 times more omega-6 than omega-3 fatty acids, but people who eat a diet high in processed foods consume a far higher ratio of omega-6 to omega-3 fatty acids (64). This imbalance is hypothesized to explain the increased incidence of heart disease, cancer, rheumatoid arthritis, autoimmune, and neurodegenerative diseases thought to stem from inflammation (65).

Increasingly in many nations, intake of the omega-6 linoleic acid comes from vegetable oils processed in ways that remove healthful components such as fiber, micronutrients, and many other phytochemicals present in unprocessed vegetables and seeds (66). Concentrated sources of linoleic acid are widely used as oils for cooking and added to processed and packaged foods. If these sources of linoleic acid are considered as supplements, people who eat diets high in processed foods are taking an equivalent of 11, 1-g capsules of linoleic acid daily over and above intake from wholesome foods. Yet, people who eat a processed diet, and ostensibly might benefit from less omega-6s, are unlikely to consume enough grassfed meat or dairy to offset their intake of omega-6s in other dietary items (67, 68).

Moreover, the benefits of consuming more omega-3 fatty acids and less omega-6 fatty acids are questionable. Historically, omega-6s were considered pro-inflammatory, but that was not the case in a review of randomized controlled clinical trials of the effects of the omega-6 linoleic acid on inflammation (69). Indeed, some studies attribute lower inflammatory markers to omega-6s (70). In an analysis of 20 prospective cohort studies from 10 countries, linoleic acid was associated with benefits for preventing type 2 diabetes and the omega-6 arachidonic acid was not harmful (71).

Interest in omega-3 fatty acids began with reports that Greenland Inuits, who ate a diet of oily fish and seal high in omega-3s, had low rates of cardiovascular disease (72, 73). Some researchers have questioned these findings because Bang et al. studied the diets of Inuits and only speculated that eating marine fats reduced cardiovascular disease (74). Other researchers emphasize Inuits had a prevalence of cardiovascular disease similar to non-Inuits; they had high mortality from cerebrovascular strokes; their general death rate was double that of non-Inuit peoples; and their life expectancy was roughly 10 years less than the Danish people Bang et al. used for comparisons (75). Nonetheless, reports by Bang et al. kindled great interest. Over 5,000 scientific papers—cited as evidence for the cardio-protective effect of the "Inuit Diet"—have explored the effects on health of omega-3s (75). Nutrition guidelines encourage people to eat fatty fish at least twice a week and to take supplemental omega-3s. Sales of omega-3 supplements are now a billion dollar industry and a marketing label for grassfed meat and dairy.

Yet, little evidence exists for the benefits of supplemental omega-3 fatty acids (75, 76). Initial trials with fish oil in Italy (77) and Japan (78) were encouraging, but subsequent studies cast doubts on their alleged benefits (79). Except for one trial (80), randomized, placebo controlled clinical trials have not shown protection against coronary events (81–86). Nor do supplemental omega-3s have any effect on the primary prevention of cardiovascular disease in people with diabetes (87). While they can improve heart function and reduce scarring after a heart attack (88), taking omega-3s preventatively does not lower risk of cardiovascular disease (89, 90), cancer (91), or all-cause mortality (92). In a meta-analysis of 10 trials, taking marine-derived omega-3s for an average of 4.4 years was not associated with reduced fatal or non-fatal coronary heart disease or major vascular events, stroke, cancer, or all-cause mortality (93). Nor does α-linolenic acid (ALA), the plant-derived precursor to eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), reliably reduce risk of cardiovascular disease (94). Taking EPA-DHA or ALA did not decrease cardiovascular events for patients with a myocardial infarction who were receiving lipid-modifying, antihypertensive, and antithrombotic therapies (81). Neither EPA nor DHA retard macular degeneration (95) or slow memory loss (96–98). Some epidemiological studies suggest DHA is associated with less risk of Alzheimer's disease, but a complete account will require placing DHA in the context of the entire spectrum of omega-3 fatty acids (99).

These findings highlight often overlooked evidence that human health is enhanced as the biochemical richness of diets increases from compounds such as EPA or DHA, to mixtures of compounds such as omega-3s (100), to foods such as oily fish that contain hundreds of compounds in addition to omega-3 fatty acids (101), to mixtures of wholesome foods such as oily fish, meat and milk, vegetables and fruits that contain tens of thousands of bio-active compounds (102). Inconsistent findings among omega-3 trials are due in part to the simplicity of compounds—for example the simplicity of EPA, DHA, or ALA—relative to the synergies that occur among all of the omega-3 fatty acids (100). That is why supplements or foods with added omega-3s do not exhibit consistent benefits, yet increased intake of fish is associated with lower inflammatory responses in people with metabolic syndrome (103). That is also why current advice is to eat oily fish rather than take supplemental omega-3s (100).

Phytochemically rich diets for herbivores and biochemically rich diets for humans include not only primary compounds—such as energy, protein, minerals, and vitamins—but the tens of thousands of other so-called secondary compounds—including but not limited to phenolics, terpenoids, and alkaloids—that in moderate amounts can have health benefits (1, 2). While any primary or secondary compound can be toxic when ingested in too high amounts, they have health benefits when consumed in moderation and in combinations as part of phytochemically diverse diets for herbivores and biochemically diverse diets for humans (1, 45). Complementarities and synergies among primary and secondary compounds within and among meals promote health.

HERBIVORE DIETS LINK MEAT AND DAIRY WITH HUMAN PALATES AND HEALTH

By providing high-quality protein and essential micronutrients such as iron, zinc, and vitamin B_{12}, meat is important in human nutrition. Nevertheless, some contend people now eat too much red meat and processed meat, which is associated in epidemiological (prospective cohort) studies with increased risk of cancer, cardiovascular and respiratory diseases, and type 2 diabetes (53, 104–106). Conversely, prospective cohort studies show reduced mortality from all causes in vegetarians (9%) and vegans (15%) compared with non-vegetarians (107), and reduced mortality of 12–20% in vegetarians compared with non-vegetarians (108).

These findings notwithstanding, a prospective cohort study of people in the United Kingdom found no reduction in mortality for vegetarians compared with non-vegetarians (109). In that study, both vegetarians and non-vegetarians had lower rates of mortality than the national average. Meat intake among non-vegetarians was a modest 79 g/d in men and 67 g/d in women, and intake of vegetables and fruit was only 20% higher for vegetarians than non-vegetarians. Eating fruits and vegetables with meat likely benefited the health of non-vegetarians.

Some contend eating too much red meat promotes oxidative stress and low-grade systemic inflammation—characterized by elevated plasma levels of pro-inflammatory markers such as C-reactive protein, serum amyloid A, tumor necrosis factor alpha, and interleukin 6—implicated in cancer, cardiovascular disease, metabolic syndrome, insulin resistance, and type 2 diabetes (110, 111). These diseases allegedly are due to ingesting excesses of compounds such as heme iron in red meat and nitrate/nitrite in processed meat (53, 112–115).

Inferring the health impacts of dietary patterns from epidemiological studies is problematical due to multiple confounding factors, many of which are not known or taken into account (116), including how the phytochemical diversity of herbivore diets affects the biochemical characteristics of meat and milk. Epidemiological studies that find inverse associations between eating red meat and health do not distinguish between meat from livestock fed high-grain diets in feedlots and livestock foraging on phytochemically rich mixtures of plants. Nor do they address how herbs, spices, vegetables, and fruits eaten in a meal with meat can enhance health.

Herbivore diets influence the flavor and biochemical richness of meat and dairy such that laboratory analyses can distinguish animals eating diets of increasing phytochemical richness, ranging from cereal grains to grain-pasture mixes to pastures (117). Among many other compounds, phenolics, carotenoids, and terpenoids in herbivore diets can enhance the flavor and biochemical characteristics of meat, fat, milk, and cheese (118). For example, tannins in herbivore diets improve the flavor of meat by reducing rumen bacteria that produce "off-flavors" from skatole, a mildly toxic organic compound produced from tryptophan in the mammalian digestive tract; tannins also affect rumen biohydrogenation of polyunsaturated fatty acids, which changes fatty acid profiles in meat (119). Adding garlic or essential oils from juniper, rosemary, or clove to the diets of lambs and calves improves the flavor of their meat and each of these plants contains a host of secondary metabolites that can benefit human health (120–122).

Phytochemical richness may be one reason why people have decidedly lower post-prandial inflammatory responses when they eat the meat of kangaroos foraging on diverse mixtures of native plants (a traditional hunter-gatherer meat meal) than when they the eat meat of wagyu cattle fed high-grain diets in feedlots (a modern meat meal) (123). Eating any food causes a transient post-prandial inflammatory response (124–126), and when people eat meat and fat, protein oxidation and lipid peroxidation cause inflammation (127). Yet, when herbivores eat phytochemically rich diets, compounds in their diets protect meat and dairy from the protein oxidation and lipid peroxidation that cause inflammation (128–130). In the study of kangaroos and wagyu cattle by Arya et al. (123), diet and animal were confounded and no studies have assessed how the phytochemical richness of forages herbivores eat affects the biochemical richness and flavor of their meat and fat and how that might affect inflammation.

Hunter-gatherers are noteworthy for their metabolic and cardiovascular health (131). They have less heart disease, cancer, diabetes, and osteoporosis than people who eat diets high in processed foods, and that is not because hunter-gatherers die before they develop these diseases (132). Although their diets are high in red meat, fat, and milk, the Maasai in southeastern Africa have less heart disease and cancer than do people who eat a diet high in processed foods (133). Nor are the diets of hunter-gatherers necessarily low in carbohydrates, as is often argued: the Hadza diet includes 16–20% honey, which is roughly 15% of their energy intake (131). Their low incidence of cardiovascular disease and obesity can be attributed in part by their higher levels of physical activity compared with people who eat diets high in processed foods (134, 135). The Maasai also add up to 28 herbs to meat-based soups and 12 herbs to milk (133). Diets of hunter-gatherers are also less energy dense and richer in fiber, micronutrients, and phytochemicals than processed diets. Findings from clinical trials and prospective cohort studies show relatively high intakes of dietary fiber and whole grains are complementary, and the prominent dose-response relationships with non-communicable diseases suggest the responses are causal (136).

Historically, Native Americans used wild berries—including but not limited to serviceberry (*Amelanchier alnifolia*), highbush cranberry (*Viburnum trilobum*), chokecherry (*Prunus virginiana*), and silver buffaloberry (*Shepherdia argentea*)—for food and medicine. Dried meat and fat were combined with berries to make pemmican, thus enabling use of dried berries during fall and winter. Berries contain rich arrays of phytochemicals that protect against metabolic syndrome, diabetes, diabetic microvascular complications, hyperglycemia, and pro-inflammatory gene expression (137). Compounds in berries improve metabolic syndrome by modulating lipid metabolism and energy expenditure. Berries contain polar compounds—proanthocyanidins, anthocyanins, and phenolic acids—that are hypoglycemic agents whose activities strongly inhibit IL-1β and COX-2 gene expression. Berries also contain non-polar compounds such as carotenoids that inhibit aldose reductase, an enzyme involved in diabetic microvascular complications. Eating fruits (and vegetables) reduces risks of type 2 diabetes, cardiovascular disease, cancer, and all-cause mortality (138, 139).

Eating antioxidant-rich fruits and vegetables with a high-fat meal improves vascular function and thwarts the negative effects of fat on endothelial function (140–142). Most plasma-borne markers of inflammation are not reliably raised after a high-fat meal, but they are reduced in many studies when meals include vegetables (143). While beneficial effects are related to antioxidant and anti-inflammatory properties, polyphenolic compounds also modulate cellular lipid metabolism and thus mitigate atherosclerotic plaque formation (144). People who eat polyphenol-rich foods, vitamin E, and calcium have less risk of colon cancer, evidently because these compounds protect against excess heme iron in red meat (145). Phytochemicals can reverse epimutations and counter all of the hallmarks of cancer

(146, 147). Collectively, these studies suggest eating vegetables and fruits, along with meat, enhances health through biochemical interactions that occur within the body during a meal—with one caveat. People who eat large amounts of vegetables high in nitrates—such as beets, celery, lettuce, radishes, and spinach—along with processed meats high in nitrates may have greater risks of disease (53), though some contend the body of evidence suggests foods enriched in nitrate and nitrite provide health benefits with little risk (148).

Cooking hamburger can generate reactive oxygen species such as malondialdehyde (MDA), a marker for oxidative stress and inflammation (149). However, adding polyphenol-rich antioxidant spices to hamburger enhances flavor while reducing meat, plasma, and urine MDA levels (150). Herbs such as rosemary and oregano enhance flavor and inhibit lipid peroxidation (151). Postprandial plasma levels of MDA rise by 3-fold after a meal of red meat cutlets, but drinking polyphenol-rich red wine along with cutlets reduces levels of MDA by 75% (152). That is one reason why red wine and red meat complement one another. Polyphenols also counteract endothelial dysfunction in people fed a high-fat diet (153). Polyphenols added to a red-meat diet fed to rats prevents lipid peroxidation in the gut and absorption of MDA into the plasma (154).

While people must eat large amounts of food to meet needs for energy and protein, phytochemically rich herbs and spices added in trifling amounts to foods enhance palatability, satiation (when a meal ends), and satiety (length of time between meals) because herbs and spices are good for health (155, 156). People eat less when food provides more sensory pleasure than they do of a blander version of the food (157). For example, people prefer the flavor and satiate more rapidly when soup is spiced with chili compared to the base soup (158, 159). These flavor-feedback relationships occur as cells and organ systems, including the microbiome, respond to primary and secondary compounds in foods (1). Nevertheless, no research has assessed how palatability, satiation, and satiety are affected by the biochemical richness of meat or dairy.

Herbivore diets influence the flavors of milk and cheese (58). For example, cattle fed diets high in lipids produce sweet, raspberry-flavored γ-dodecalactone from oleic acid and sweet, raspberry-flavored γ-dodec-cis-6-enolactone from linoleic acid; cattle fed diets low in lipids produce milk fat high in cheesy-flavored fatty acids and precursors of the blue-cheese-flavored methyl ketones and coconut-peachy-flavored δ-lactones (160). Among many other compounds in forages, carotenoids impart a yellow color and they positively influence the flavor of milk and cheese. Terpenes also positively influence flavor of milk and dairy products derived from native pastures with diverse species of grasses, forbs, and shrubs that produce many more terpenes than do monocultures of grasses. Plant diversity also affects phenolics in cheeses such as L'Etivaz and Gruyere (161, 162).

When dairy cows graze botanically diverse swards, rather than a total-mixed ration of cultivated forages and grains, both the flavor and biochemical richness of their milk and cheese are greatly enhanced, and local peoples prefer the flavors of milk and cheese from dairy cows grazing on the botanically diverse swards (163, 164). Consumers in countries such as Italy and France select cheeses based on season of production and the related mix of plants in particular landscapes—for example, cheese made from high elevation summer pastures in the Alps—their palates linked locally with soil, plant diversity, and herbivore diets (165). Compared with trained evaluators, untrained evaluators, who typify naïve consumers, are less able to distinguish and savor differences in milk and cheese, which illustrates how past experiences influence palatability. More research is required to elucidate how herbivore diets affect biochemical richness and palatability of milk and cheese (58).

As with milk and cheese, people prefer meat they are accustomed to eating (166). When Spanish milk/concentrate-fed lambs and British grassfed lambs were assessed by Spanish and British taste panels, both panels found British lamb had higher flavor intensity, but the Spanish panel preferred milk/concentrate-fed lambs, while the British panel preferred grassfed lambs (167). Families in Mediterranean and Northern European countries—Greece, Italy, Spain, France, UK, and Iceland—also differ in their preferences for meat depending on whether they are accustomed to eating lambs fattened on grain or on pastures (168). Most Americans are conceived and raised eating grain-fed beef, so taste panels of consumers, as well as experts trained to evaluate sensory features of meat, typically find grain-finished beef more palatable than grass-finished beef (169–171). Inconsistent ratings for grass-finished beef in studies reflect differing past experiences of consumers and differences in how animals are finished. Collectively, these studies show why the generic label "grassfed" tells a consumer little about how the phytochemical richness of the diet contributes to flavor or health (59–61, 172, 173).

BIOCHEMICALLY RICH DIETS AND ENVIRONMENTAL HEALTH

As humans transitioned from hunter-gatherers to farmers, ranchers, and urbanites, our diets shifted to include more highly processed foods, refined sugars and fats, and meat. How we produce food is adversely affecting food quality, both the phytochemical richness of herbs, spices, vegetables, and fruits and the biochemical richness of meats (1, 172), In turn, the foods we consume are adversely affecting health, as illustrated when researchers compared four diets (8): (1) Vegetarian—vegetables, fruits, grains, sugars, oils, eggs and dairy, and normally not over one serving a month of meat or seafood; (2) Pescetarian—vegetarian diet with seafood; (3) Mediterranean—vegetables, fruit, seafood, grains, sugars, oils, eggs, dairy and modest amounts of poultry, pork, lamb, and beef; and (4) Omnivorous—includes all food groups, for example the 2009 global-average diet and the income-dependent diet projected for 2050, which is essentially a diet that includes many processed foods high in refined carbohydrates, refined fats, oils, and meats.

Compared to the omnivore diet, the other three diets had a lower incidence of type II diabetes, (16–41%), cancer (7–13%), mortality from coronary heart disease (20–26%), and mortality from all causes combined (0–18%) (8). When a projected population increase to 9.7 billion people is combined with a projected increase of 32% in per person emissions from shifts to an omnivore diet, the net effect is an estimated 80% increase in global GHGE from food production by 2050. Alternatively, net GHGE from food production would not increase if the global diet was vegetarian, pescetarian, or Mediterranean. These diets could ostensibly reduce GHGE below those of the projected 2050 income-dependent diet, with reductions of 55, 45, and 30% for vegetarian, pescetarian, and Mediterranean diets, respectively. These findings are similar to other systematic reviews that assessed the impacts of diets on GHGE, land use, water use, and health (174).

Life cycle assessments suggest plant foods have less GHGE than do animal foods, and ruminant meats have greater GHGE per gram of protein than poultry, pork, eggs, dairy, non-trawling seafood, and traditional aquaculture (16, 175). Yet, those assessments generally do not address nuanced relationships among the health of soil, plants, herbivores, and humans (57, 176). When the environmental footprint—expressed both as land use for production and as GHGE—of plant and animal foods is calculated to consider essential amino acids in required amounts, animal foods are similar to most plant foods due to the higher quality of animal proteins (177). Grass-finished livestock can also promote nutrient cycling, soil carbon sequestration, and clean water and support food security (178–180).

Worldwide, agriculture involves 570 million farms and ranches—over 90% of them managed by a family and reliant on family labor—that produce 80% of the world's food (181). Agriculture employs over 1.3 billion people, nearly 40% of the global workforce (181). In nearly 50 countries, agriculture provides work for 50% of the population, up to 75% in poorer nations. Production of meat and dairy from cattle, sheep, and goats provides job security and food from animals that graze land unsuitable for farming and eat crop residues (179, 180). Livestock convert more than 432 billion kg of food/fiber byproducts inedible by humans into human-edible food, pet food, industrial products, and 4 billion kg of N fertilizer (182). In the U.S., 2.2 million farms and ranches cover 922 million acres; agriculture employs 1.6 million people and produces $31.8 billion in exports; and animal-derived foods provide considerable energy (24%), essential fatty acids (23–100%), protein (48%), and amino acids for people (34–67%) (182).

Due to low yields of beef from extensive grazing, people in Brazil are considering converting pastures to cropland for soybeans or to sugarcane for ethanol, but intensifying grazing can help meet projected 80% increases in demand for beef by 2050. Compared with crops, intensifying grazing management produces greater ecological benefits, including enhanced soil health and carbon sequestration (18, 55). Some nuances of these relationships are illustrated by comparing biological type of cattle—small (3) or large (5) frame sizes—and nutritional regime. Cook et al. (183) found that large-frame steers ate more forage, gained weight more rapidly, and were heavier at slaughter than small-framed animals when they were finished in feedlots, but when they were finished on forages, small-framed animals were in better body condition. Outcomes depended on nutritional regimen—finished in feedlots; fed native range (short-grass prairie in eastern Colorado) yearlong; fed native range complemented by crested wheatgrass in spring; fed native range accompanied by crested wheatgrass in spring and forage sorghum in late summer and winter. Grazing complementary forages increased beef production per hectare by 53% compared with grazing only native range. During a 97-day finishing period in feedlots, feed efficiency (kg feed/kg gain) and weight gain declined significantly during the last 31 days, a time when weight gain was mainly fat and little protein. Energy inputs lost in producing carcasses with excessive cut-away fat were important, as roughly 91% of the energy for feedlot finishing was for feed production. Compared with forages, feeding concentrates was expensive. The opportunity is to create grazing-based livestock-production systems based on phytochemically diverse forages for specific ecoregions at temporal and spatial scales that enhance livestock production and ecological services (184).

Of 80 ways to mitigate climate change, regenerative agriculture—managed grazing, silvopasture, tree intercropping, conservation agriculture, and farmland restoration—jointly rank number one as ways to sequester GHG. Silvopasture systems that combine growing trees with managed grazing rank ninth while managed grazing ranks nineteenth (31). The impacts of managed grazing are due to benefits that accrue through enhanced plant health and diversity over vast grazing lands (20, 185). Long-term storage of carbon in soil with silvopasture can be five times more than with managed grazing alone, not including carbon stored in trees (186–188). Silvopasture delivers efficient feed conversion, enhanced biodiversity, improved connectivity among habitats, and enhanced animal welfare (19). Grasses, forbs, and shrubs add resilience to silvopasture systems in the face of rising temperatures, drought, and fires, which are causing some forests, unable to cope with changing climates, to die and transform from carbon sinks to carbon sources (189). In addition to sequestering carbon, emissions of methane and nitrogen can be reduced when ruminant diets contain tannins and saponins common in forbs, shrubs, and trees (190–192). The notion that regenerative agricultural practices can markedly influence climate is consistent with evidence that carbon uptake from the atmosphere by native plants, which invaded abandoned farms following massive depopulation of the Americas following European arrival, contributed to global cooling during the Little Ice Age (193).

UPSHOT

Circumstantial evidence supports the hypothesis that plant diversity—manifest as phytochemical richness of landscapes—affects the biochemical richness of meat and dairy as well as human and environmental health. Future studies should elucidate how plant diversity influences flavor and biochemical richness of meat and dairy; how phytochemically rich herbs, spices, vegetables, and fruits complement meals that contain meat; and how the aforementioned affect the health of people and the planet. Findings from these studies can achieve three ends. First, they can reveal relationships among liking for the flavor of meat and dairy; the ability of phytochemically and biochemically rich meals that contain meat and dairy products to satiate; and the value to cells and organ systems, including the microbiome, of phytochemically and biochemically rich foods for humans. Second, they will underscore why more money and effort ought to be spent creating human and environmental health by growing and eating wholesome foods and less effort spent treating symptoms of diet-related diseases. Finally, they will help people appreciate how the foods we eat reflect our relationships with land, water, and air, enabled by plant diversity across landscapes, thus revealing how palates link soil and plants with animals and environments.

While the Anthropocene is a curse for the havoc it is reeking globally on populations of plants and animals, including humans, it is a blessing because *Homo sapiens* may finally come to appreciate the crux of Aldo Leopold's land ethic (194). We are members of natural communities: what we do to them, we do to ourselves. Only by nurturing them can we nurture ourselves. Palates link cultures with landscapes and moderating the impacts of palates on human and environmental health will require changes in the kinds of foods we produce and consume, how we produce food, and how we reduce food waste, which is 40% of food produced annually and a major contributor to GHGE (31, 195–197). That will necessitate collaboration among food producers, food industry, nutritionists, ecologists, health professionals, educators, and policy makers with support of consumers. Forsaking diets high in processed foods will be challenging, but that can be facilitated if consumers appreciate the influence of diet on human and environmental health (16). These transformations can occur socially, economically, and ecologically by growing wholesome foods—plants and animals—as the basis for meals that nourish the health of people and the planet (1, 21, 22, 24).

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Overview of Some Recent Advances in Improving Water and Energy Efficiencies in Food Processing Factories

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Rapid development of food factories in both developed and developing countries, owing to continued growth in the world population, plays a critical role in the food supply chain, including environmental issues such as pollution, emissions, energy and water consumption, and thus food system sustainability. The objective of this study was to briefly review various environmental aspects of food processing operations, including aquatic, atmospheric, and solid waste generation, and also to discuss several strategies that many companies are using to reduce these negative impacts as well as to improve water and energy efficiency. To obtain higher energy efficiencies in food processing factories, two key operations can play critical roles: non-thermal processing (e.g., high pressure processing) and membrane processes. For higher water efficiency, reconditioning treatments resulting in water reuse for other purposes can be conducted through chemical and/or physical treatments. With regards to reducing volumes of processing food waste, two approaches include value-added by-product applications (e.g., animal feed) and/or utilization of food waste for energy production. Finally, we present trends for lowering operational costs in food processing.

Keywords: food, energy, water, sustainability, efficiencies

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INTRODUCTION

Ever-increasing population growth has resulted in higher demand for food, which has led to rapid change and expansion in the number of food factories. It was discussed in the 2009 World Summit on Food Security that by 2050, global food production should rise by at least 70% to feed growing populations (anticipated to be 9 billion people) (1). There are different environmental inputs (e.g., land, water, and energy) and outputs through food systems including raw material/agricultural production, food processing, packaging, distribution, retail, consumption, and end of life. Therefore, all food processing—in addition to food production—results in other problematic outputs such as greenhouse gases, wastewater, as well as packaging and food waste.

Key environmental impacts from food include aquatic, atmospheric, and solid waste generation, which are influenced by the quantity of resources utilized (including energy and water), waste generated, and transport used (truck, train, plane, etc.) in the food system (2). These environmental changes are expected to affect food security and contribute to decreasing the quantity, quality and affordability of food all around the world (3). Management of energy, water, and other resources can lead to increases in efficiency, cost savings, and the minimizing of negative environmental impacts (2).

Energy efficiency policies, which are closely linked to several issues including energy security, climate change, and economic objectives have been paid attention recently (4). For higher energy efficiency achievement, several approaches could be used: firstly, replacement of conventional methods with new technologies (e.g., application of high-pressure processing instead of conventional heating); secondly, membrane processing application instead of energy-intensive operations (e.g., evaporation); and finally, using some technologies for energy production from food waste such as biological, thermal, and thermochemical technologies. The purpose of this review paper is to highlight some environmental impacts of food processing and to discuss some solutions to address these issues.

ENVIRONMENTAL IMPACTS OF FOOD PROCESSING

Aquatic Effects

Water is a vital component in the majority of food processing, and its consumption is of great consideration owing to the high-quality water utilized during the manufacture of food products as well as generation of significant volumes of pollutant wastewater. Domestic and industrial water demand have been increasing due to population growth, demand for products, and economic growth, as well as dietary changes into higher animal protein consumption (5). It was determined that a meat-based diet has a larger water footprint (∼36% larger) compared to a vegetarian diet (6). For example, the production of 1 g of animal protein from egg, milk, or meat requires ∼29, 31, or 112 L of water, respectively; however, 1 g of cereal protein requires 21 L of water (7).

During food processing operations, water is used in many unit operations and applications, including as an ingredient, an initial and intermediate cleaning source, or as an efficient transportation mechanism for some raw materials, and is a key agent utilized in sanitizing plant equipment and areas. Water use will likely continue to be a critical component of the food industry, but it has become a target for efficiency and reduction efforts (8).

Agriculture and food processing can affect water quality via chemistry (e.g., heavy metals, including lead, arsenic, iron, etc.) and bacterial aspects (such as coliforms and *Streptococci* spp.) (9). When discharged into the environment, water containing chemical and/or microbial pollution can negatively impact aquatic life. Heavy metals are a risk to fish, and subsequently to human health (10)—so much so that limits for consumption of some types of fish have been recommended by health agencies. Furthermore, irrigation of crops with polluted wastewater may be problematic, as absorption of the pollutants by growing vegetables, fruits, or other crops, may ultimately lead to contaminants becoming part of the human food supply chain, and thus wastewater may actually be considered a risk factor for human health (9).

Atmospheric Effects

The main reason for atmospheric emissions from the food industry is extensive energy usage. The majority of energy consumption occurs during the heating of buildings, powering different processes, sterilization, transportation of raw materials and products, and other unit operations. Use of conventional fossil fuels may decrease through increasing the use of renewable energy (e.g., geothermal, wind, or solar energy) (11). Emissions of CO_2 are predicted to rise significantly in the next 20 years if the production and use of traditional energy via the burning of fossil fuels continues to increase. Increasing levels of CO_2 in the atmosphere eventually overwhelm the natural carbon cycling by oceans and forests and have driven atmospheric CO_2 concentrations far above pre-industrial levels. It is thus probable that global temperatures will increase by at least 1.0–3.5°C (12).

Another key parameter leading to atmospheric pollution from the food industry is product transport. The effect of transport depends on various parameters such as the mode of transport, the type, age and condition of vehicles, and the delivery distance.

Further, agricultural activities (which produce most of the raw food products) lead to various air emissions, which will further exacerbate global warming, and include emissions of ammonia, methane, nitrous oxide, as well as sulfur and dust particulate, especially PM_{10} (a mixture of dust, smoke, soot, salt, acids, metals, and other fine particles) (13). Additionally, during fermentation and decomposition of organic materials, as well as during combustion of fossil fuels, volatile organic compounds (VOCs) are produced, which can contribute to ozone formation when combined with nitrogen oxides (NOx) and sunlight (14, 15). Some VOCs also result in negative health effects such as eye, nose, and throat irritation.

Food processing and packaging of raw materials can cause significant air pollution. Apart from air emissions due to fossil fuel combustion, indoor organic dust pollution is unique to this sector (16). Dutkiewicz et al. (17) carried out a study in which air samples for the determination of concentrations of microorganisms, dust and endotoxin were collected at 6 sites in the division producing potato flakes and meal from dried potato pulp and at 2 sites in the division producing potato syrup from imported starch. The concentrations of total airborne microorganisms were within a range of 28.3–93.1 × 10^3 cfu/m^3. Mesophilic bacteria were dominant at all sampling sites, forming 73.1–98.8% of the total count. Its airborne concentration increased rapidly after the peeling of potatoes and attained maximal values at cutting and blanching (steaming and sulfuration) of potatoes, and at sacking of potato meal. Several studies also confirmed high levels of particles in food processing industries, such as bacteria, endotoxin, and occupational antigens in places like breweries (18) and sugar-beet processing plants (19).

Solid Waste Generation

It has been reported that ∼1.3 billion tons of food products, such as fresh fruits, vegetables, meats, bakery, and dairy products, are lost along the food supply chain (20). Another estimation indicated that in the United States, about 40% of food produced is lost as waste during processing and distribution by retailers, restaurants, and consumers (21). Additionally, it has been projected that food waste in the European Union will increase from 89 million tons in 2006 to 126 million tons in 2020 (22).

Food processors are substantial waste producers, as they can generate considerable quantities of solid waste (food waste, packaging, etc.) and various liquid effluents (23). These processing wastes can include fruit and vegetable residues, discarded fruits and vegetables, molasses and bagasse from sugar refining, bones and blood from meat and fish processing, non-fermentable residues from wineries, distilleries, and breweries, wastes from dairy factories (e.g., cheese whey), and wastewaters from various unit operations such as washing, blanching, and cooling (24). The disposal of these types of food wastes into the environment should be avoided due to several reasons, including poor biological stability, considerable concentrations of organic components, poor oxidative stability, and significant nutritional value which can be lost from the human food chain. Additionally, a high amount of food waste coupled with microbial decomposition can result in adverse effects on the environment as well as human health (25). To minimize environmental burdens due to food waste, and also to lower the risks to human health, proper management, recycling, and value-added applications are necessary (24).

Many food wastes mostly consist of various carbohydrates (such as starch, cellulose, and hemicellulose), lignin, proteins, and lipids, as well as various organic acids and minerals (ash). Due to the generally high carbohydrate composition of these wastes, the production of renewable energy may be a viable alternative to landfilling. Apart from energy generation, most food wastes contain compounds that could be used as substrates and nutrients for various microbial and enzymatic processes (26, 27). Additionally, utilization of food waste can lead to improvement in the bottom line for both the company and for the locality, and can lead to lower environmental pollution and/or pressure.

STRATEGIES FOR ENVIRONMENTAL IMPACT REDUCTION

There are many opportunities to improve the environmental footprint of food processing operations. Three of these include improving energy efficiency, water efficiency, and waste reduction (**Figure 1**), which will be discussed in this paper. There are many more that are not considered in this paper, however, and the reader is referred to other papers in this Research Topic [e.g., (28, 29)].

Energy Efficiency

Non-thermal Processing

One challenging topic for all food processing sectors has always been energy efficiency enhancement; illustrating this point, the food industry was classified as the fifth biggest consumer of energy among 20 manufacturing sectors in US in 2002 (30). Depending upon the type of products produced, a great quantity of energy is often applied during the conversion of raw substances into higher-value food products (31). For example, to evaporate 1 kg of water from products, an average of 6 MJ of heat is needed during drying process; however, to reduce the temperature of products under −20°C, 1 MJ (or 0.3 kWh) of electricity is required during freezing processes (8). In this regard, heating processes are often the most energy-intensive types of unit operations used in the food industry, and can include pasteurization, sterilization, dehydration, evaporation, and drying. In conventional heating methods, heat is transferred to the food material via conduction, convection, and radiation heat transfer. Often, the movement of heat from the surfaces of the materials toward their centers is considered a limitation for thermal treatment due to relatively slow heat transfer through food products. However, other effective techniques for heat transfer by using newer technologies (e.g., molecular interactions via microwave) are gaining acceptance (31). Applications of these newer methods not only results in better energy utilization and heat recovery, but can also improve the overall sustainability of food production as well as the nutritional quality of final products (32).

Non-thermal methods are also gaining popularity. These techniques offer several advantages to food manufacturers, such as minimizing the impact on nutritional and sensory properties of food products, they can extend shelf life by preventing or destroying microorganisms, and they can be more energy efficient as well (33). In addition to saving energy by applying these technologies, most of these new approaches also result in water savings, increased reliability, lower energy required (and thus lower emissions), and improved product quality (34). Some of these emerging methods include high pressure processing (HPP), ultrasound (US), pulsed electric fields (PEF), and pulsed light treatment (PL) (35). **Table 1** summarizes the effects of the application of several non-thermal technologies on energy efficiency improvement, and will be discussed below.

During HPP, momentary pressure within the range of 300–700 MPa is transmitted throughout the food products, resulting in a reduction of processing time and consequently energy consumption (47, 48). To compare application time and temperature between HPP and conventional processing, (36) reported that HPP (600 MPa/20°C/60 s) resulted in a lower microbial population throughout 12 weeks, and hence a greater shelf life than thermal pasteurization (65°C for 1 min and 85°C for 25 s). Another study found that HPP (400 and 600 MPa/5 min/20°C) was a better alternative for apple processing vs. conventional pasteurization (75°C/10 min) (37). In terms of processes such as chilling and freezing, there is an obvious reason for lower energy consumption during HPP than conventional methods because, during the phase change during HHP, the latent heat of water is nearly 30% lower compared to that at atmospheric pressure (49). Due to water expansion during freezing, pressure increments can lead to lower freezing points (50). HPP can be used to use pressure to induce freezing and thawing, so that the growth kinetics of ice crystals results in a finer crystal structure within the food matrix (51, 52).

Ultrasound (US) is energy generated by sound waves (53) and has shown high potential for increased heat transfer and faster cooking rates compared to conventional cooking methods (54). The main mechanism of action is cavitation. When air bubbles implode, high localized pressures and temperatures occur, and can reach 50 MPa and up to 5,000°C (55) (**Figure 2**).

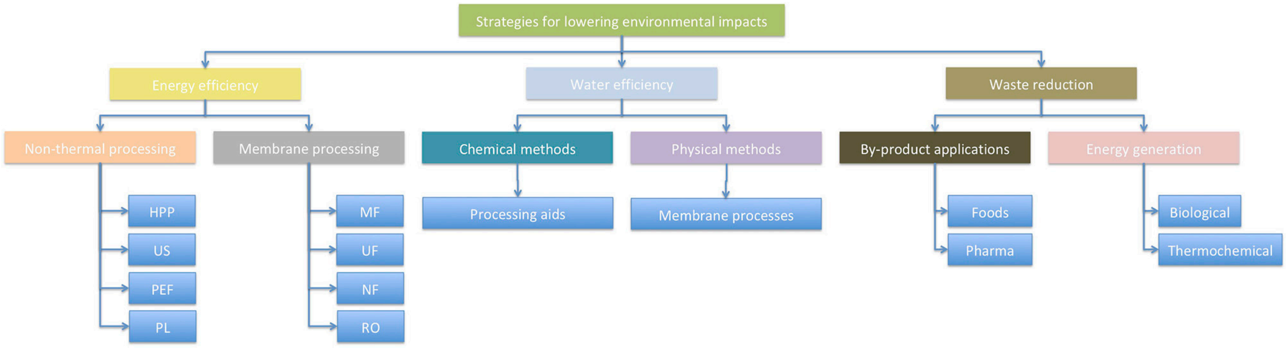

FIGURE 1 | Examples of three options for improving energy and water sustainability in food factories.

Efficacy depends upon the food matrix and upon the intensity of the US; heat transfer improvement of about 30–60% has been seen (57). The main advantage to using US is the fact that temperatures are generally between 40 and 50°C during ultrasonic pasteurization, which are considerably lower than the temperatures used in conventional pasteurization processes. In this regard, it has been reported that *Escherichia coli* and *Saccharomyces cerevisiae* were reduced by more than 99% after ultrasonication, whereas *Lactobacillus acidophilus* was reduced by 72 and 84% depending on the media used (58). Hence, the resistance to ultrasound treatment of spores and Gram-positive and coccal cells is higher than vegetative, Gram-negative and rod-shaped bacteria. Ultrasonication combined with heat was applied to examine the inactivation of *Listeria innocua* and mesophilic bacteria in raw whole milk (59). A combination of US and heat led to an increase in the kill rates compared to the rates of thermal treatment alone, and a synergistic rather than an additive effect was observed. Zhu et al. (60) demonstrated that the use of ultrasound (21.2 kHz, 2 min) enhanced the efficacy of selected sanitizers (such as water, chlorine, acidified sodium chlorite, peroxyacetic acid, and acidic electrolyzed water) in reducing *E. coli* O157:H7 populations in spinach.

Use of US to preserve the nutritional and sensory properties of various food products has been widely evaluated (61–63). In terms of drying processes, combinations of US with moderate heat can result in significant reductions of both processing temperature and processing time compared to the use of air-drying alone. (38) found that the time required to dry carrot slices decreased from 35 min to 25 min when using air-drying alone at 60°C vs. air-drying combined with US at the same temperature. Ortuño et al. (64) conducted an experimental study on the convective drying kinetics of orange peel slabs (thickness 5.95 ± 0.41 mm) at 40°C and 1 m/s with and without power ultrasound application. Obtained data indicated that ultrasonic application influenced both internal and external mass transport. Kek et al. (65) evaluated ultrasound pre-osmotic treatment prior to hot-air drying of guava slices. According to the results, ultrasonic pretreatment lowered the drying time by 17–33%, increased the effective diffusivity by 18–35%, and increased the drying rate constants of guava slices by 37–42%.

In fact, there are several advantages to using US for food processing instead of conventional processing; these may include more effective bulk mixing and micro-mixing, faster heat transfer, better mass transfer, decreased thermal and concentration gradients, reduced processing temperatures, smaller equipment size, faster start-up, smaller production increments, and reduction in the number of processing steps (7).

Pulsed electric field (PEF) can be an effective inactivation method for microbial cells when it is combined with low to moderate processing temperatures (<50°C) through inducing permeabilization of biological cells. During this process, tissues are exposed to an electrical field [typically a very short timeframe (μs)] and high-voltage (kV) pulses (**Figure 3**). Effectiveness depends on the electric field strength, applied temperature, processing time, and energy input (67). Heinz et al. (39) evaluated the effect of temperature (35–70°C) on the lethality of PEF for *E. coli* contamination in apple juice. They observed a negative correlation between energy requirements and treatment temperatures. To obtain a 7-$\log_{10}$ inactivation of *E. coli* at 24 kV/cm, the energy requirements declined from 160 to 100 kJ/kg, with a temperature increment of 40 to 50°C. Additionally, it was reported by Korolczuk et al. (40) that, for *S. enteritidis*, by increasing pulse width from 0.05 to 1 μs during PEF processing (50 kV/cm and 15°C), a lower amount of energy (from 44 to 32 kJ/kg) was required. Further, the application of PEF (3–5 kV/cm, 1.6 μs pulse duration, 40–80 pulses) for sugar beet dehydration led to a lower level of force being required for beet slicing (from 16 to 8 N), which then decreased the total energy requirement for processing (41). Another study also confirmed that PEF (7 kV/cm, 1.5 μs pulse duration, 40–80 pulses) resulted in more than 50 % energy savings compared to traditional methods for the drying of plants (i.e., grass, maize, and lucerne) (42).

PEF has been used before and during drying processes because of improved mass transfer and localized structural changes of cell membranes, as well as an increase in membrane permeability (68, 69). It has been shown that drying of red pepper at 45°C takes 4.9 h, but after PEF pre-treatment (2.5 kV/cm, 100 Hz, 4 s), drying time was reduced by 35% (43). Another recent investigation optimized PEF pre-treatment of radish (1.446 V/cm

TABLE 1 | Examples of energy efficiency improvements by non-thermal processing applications*.

Method	Process conditions	Key results	References
HPP	Pressure: 600 MPa Temperature: 20°C Time: 60 s	Compared to thermal pasteurization (65°C for 1 min and 85°C for 25 s), HPP resulted in longer shelf life and lower microbial population over 12 weeks.	(36)
	Pressure: 400 and 600 MPa Temperature: 20°C Time: 5 min	Final apple product of HPP indicated better results including higher fresh-like, value-added products with reasonable shelf life rather than conventional pasteurization (75°C/10 min).	(37)
US	Frequency: 20 kHz Power capacities: 100 w Max time duration: 40 min	US application directly coupled to the food samples led to optimum energy transfer for food dehydration.	(38)
PEF	Temperature: 35–70°C Electric field strength: 8–40 kV/cm Energy input: 5–120 kJ/kg Pulse repetition rate: 2–95 Hz	A significant reduction was observed in energy consumption from 160 to 100 kJ/kg by higher temperature (from 40 to 50°C) during achievement a 7-log10 inactivation of *E. coli*.	(39)
	Temperature: 4–20°C Electric field strength: 30–80 kV cm Pulse frequency: 1–815 Hz Energy input: 0–300 kJ/kg Pulse width: 0.05, 0.1, 0.25, 0.5, 1, 2 and 3 μs	Lower energy consumption (from 44 to 32 kJ/kg) was observed for destruction of *S. enteritidis* through increasing pulse width from 0.05 to 1 μs.	(40)
	Electric field strength: 3–5 kV/cm pulse duration: 1.6 μs 40–80 pulses	Owing to lower force required for a beet slicing by PEF application, total process energy requirement reduced.	(41)
	Electric field strength: pulse duration: 1.5 μs 40–80 pulses	For drying plants such as grass, 50 % energy saving was achieved by PEF rather than traditional methods.	(42)
	Electric field strength: 1.0–2.5 kV/cm Pulse frequency: 100 Hz Pulse width: 30 μs	PEF as a pretreatment led to time reduction of drying the red pepper by ~34.7%.	(43)
		PEF application as a pretreatment for drying crystal radish indicated higher drying rate and lower drying time and energy consumption.	(44)
PL		PL treatment for 3 s resulted in 7.29-log CFU/ml reduction of *E. coli* inoculated in apple juice.	(45)
		The population of *L. innocua* was reduced by 1.39 log CFU using PL treatment and there was no significant growth after 8 days of storage at 4°C.	(46)

**HPP, high pressure processing; US, ultrasound; PEF, pulsed electric field; PL, pulsed light treatment.*

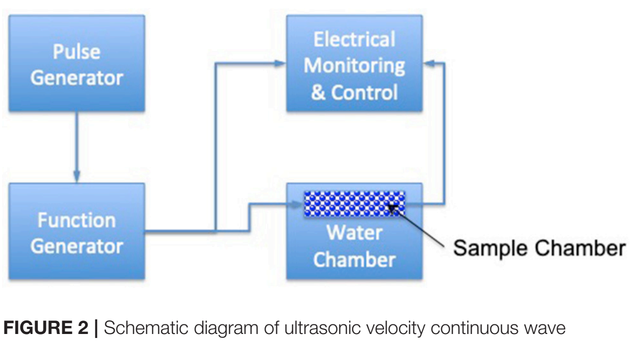

FIGURE 2 | Schematic diagram of ultrasonic velocity continuous wave technique [based upon (56)].

for 28 μs, and 87 pulse), and found an improvement in the drying rate by 26% and a reduction of the drying time by more than 14%, leading to reduced energy consumption (44). When used in conjunction with conventional drying, PEF pre-treatment resulted in decreased drying time by up to 50%, and drying temperature did not exceed 60°C. A reduction of drying time and/or drying temperature can result in a considerable reduction in energy consumption (70, 71).

Pulsed light (PL) processing is an energy-saving, waste-free and environmentally friendly technology. Light pulses are based on electromagnetic energy, which is accumulated in a capacitor and then released in the form of light within a very short time (ns or ms); therefore, this process results in an amplification of power with a minimum of energy consumption. Several studies have been conducted to determine microbial population reduction for several organisms using PL treatments. For example, *E. coli*-inoculated apple juice was lowered by 7.29-log CFU/ml after 3 s of a PL treatment using 88,000 mJ/cm^2 (45). Cold pasteurization of milk was treated by PL with a minimum dose of 12.6 J/cm^2 delivered in 56 s (72). In 2009, Uesugi and Moraru used PL (9.4 J/cm^2) to reduce *L. innocua* on the surface of sausages, and found a 1.39 log CFU reduction after PL treatment, and found no growth after 8 days of storage at 4°C.

Membrane Processes

A highly energy intensive unit operation is evaporation; it is commonly carried out by mechanical vapor recompression technology. However, a good alternative for energy efficiency enhancement is membrane filtration, with a potential energy savings of 30–50% compared to distillation and evaporation (73). The principle of membrane filtration is based on forcing liquid food through a membrane whereby, after a determined processing time, two different streams are obtained, including permeate (material passing through the membrane) and retentate (concentrate rejected by the membrane) (8) (**Figure 4**). There are four groups of membrane processes based on membrane pore size, consisting of microfiltration (MF) (0.2 to 1 μm), ultrafiltration (UF) (0.02 to 0.1 μm), nanofiltration (NF) (0.001 to 0.01 μm), and reverse osmosis (RO) [<0.001 μm (75, 76)].

Energy consumption of membrane filtration is ∼14–36 kJ/kg of water removed, compared to evaporation with mechanical vapor-recompression of 50 kJ/kg of removed water. Processing hot feed and recovering heat in the hot permeate (via heat exchangers) is another energy saving method that is commonly employed with membrane filtration (73). However, one limitation of this process is reported to be relatively low dry weight yields (12–20%), hence a hybrid process consisting of membrane filtration and evaporation is often utilized specially in the dairy processing industry (77). Another potential disadvantage is fouling of the membrane as a result of different compounds, including salts, sugars, proteins, and fats present in the food material. Fouling leads to higher energy consumption and reduced processing efficiency; therefore, to address this challenge, regular cleaning with caustic solutions is typically required (78).

Membrane technology can be applied alone or in combination with other unit operations, such as distillation and evaporation, in order to concentrate various dilute solutions (e.g., grain milling, vegetable oil extraction, sugar manufacturing, etc.). By using membrane systems to remove water in corn wet milling, about 90% energy savings have been reported by Rausch (79) because of no need to provide heat for phase change. Considerable energy (electricity) is needed for pumping to produce high transmembrane pressure and recirculation; thus the total energy balance should be carefully studied (8). However, it has been recently reported that there are new operating conditions that use renewable energy sources coupled with forward/reverse osmosis to promote water recovery from low-strength wastewater. In this regard, anaerobic acidification and forward osmosis (FO) membrane were simultaneously integrated into an air-cathode MFC (AAFO-MFC) for enhancing bio-electricity and water recovery from low-strength wastewater (80). During a long-term operation of ∼40 days, the AAFO-MFC system achieved continuous and relatively stable power generation, and the maximum power density reached 4.38 W/m^3. The higher bio-electricity production in the AAFO-MFC system was mainly due to the accumulation of ethanol resulting from the anaerobic acidification process and the rejection of FO membrane. In addition, a proper salinity environment in the system controlled by the addition of MF membrane enhanced electricity production. These results substantially improve the prospects for simultaneous wastewater treatment and energy recovery. The use of most renewable sources of energy (e.g., hybrid renewable energy sources and battery storage) can also be coupled to produce high transmembrane pressure and recirculation in membrane systems (81). There are other benefits in membrane application, such as selectivity, ease of system operation, lower operating, maintenance, and manufacturing costs compared to heating processes and a better-quality product due to low processing temperatures (i.e., room temperature) (82, 83).

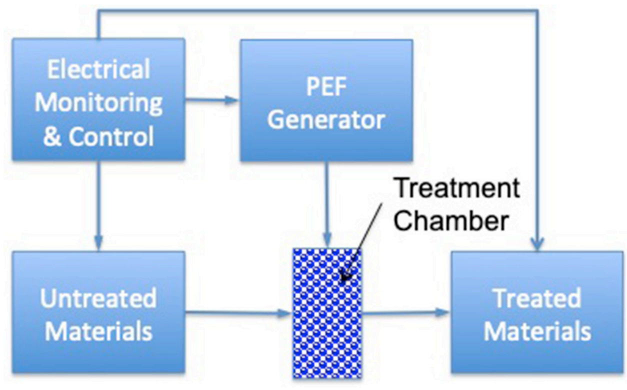

FIGURE 3 | Schematics of a PEF processing system for pumpable products [based upon (66)].

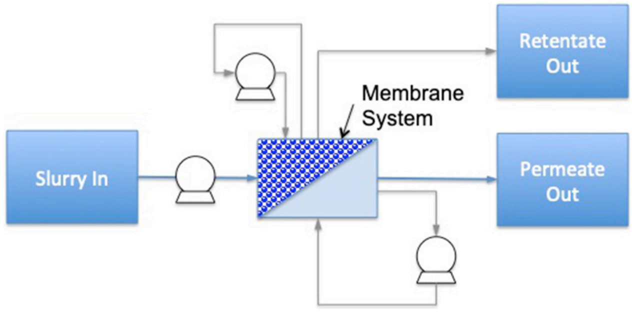

FIGURE 4 | Diagram of a membrane filtration system including cross-flow and flux enhancement. Dotted lines identify the boundaries for system analysis; circles with symbols identify the processing control measurements needed for energy calculations (light gray are optional measurements), the dark gray area illustrates the treatment chamber and darker shapes the food material. Additional system components are named individually [based on (74)].

During soybean oil extraction with hexane, the raw extract usually consists of both soybean oil (25–30%) and hexane (70–75%) (84). In a common industrial practice, distillation of the remaining hexane consumes most of the energy cost; however, the application of ultrafiltration or reverse osmosis can lead to substantially reduced energy consumption for hexane evaporation and reduced thermal damage as well (85).

In sugar factories, sugar thin juice obtained from filtration is entered into an evaporation step to concentrate sugar solution.

To reduce thermal energy consumption of sugar dehydration, Madaeni and Zereshki (86) used a two-stage RO system for preconcentration of sugar thin juice. They concluded that use of this system prior to final concentration in evaporators resulted in a 33% energy savings.

Water Efficiency

Pressure on limited water reserves has led to the efforts of many governments and water authorities to improve water use efficiency and to encourage water conservation. There are considerable differences in water consumption amongst various food factories. For example, high water users in the food industry include meat, dairy, and fruit and vegetable processors. By contrast, bakeries and grain producers, which are mostly involved in dry processes, can be categorized as relatively small water users (87). Apart from food processors and their water consumption, there are always some benefits to higher water efficiency.

For example, the Australian Government carried out a survey on manufacturing groups and reported a large savings on total water usage of up to 25, 30, and 60% through the use of basic initiatives such as behavioral changes, water recycling (without conditioning treatment), and water use monitoring, respectively. Other substantial savings were also observed by technology changes (36%) and product redesign (72%), both of which require time and investment (88). The first action before conducting reconditioning treatments for wastewater should be water use reduction, because this approach requires lower training and investment, and the volume and strength of the wastewater are also directly altered (5).

Reconditioning treatments for wastewater include various physical processes, chemical processes, or a combination of both types of treatments. These are commonly used to decrease microbial levels and to eliminate hazardous chemicals in water streams. During chemical treatments, several processing additives may be applied, including chlorine, chlorine dioxide, chloramines, ozone, hydrogen peroxide, or peracetic acid (89). On the other hand, for physical treatments, membrane systems can be used to recover various valuable by-products from wastewater streams (e.g., protein or lactose from whey) (5). Membrane systems for reconditioning wastewater can include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). These are used for specific ranges of particle sizes. In practice, application of MF for wastewater can separate microbes; UF can be used to remove microbes and suspended solids, however RO can separate microbes, suspended solids, and even some dissolved solids (90).

Water reuse offers great opportunities for lessening groundwater depletion but it does have challenges, such as balancing supply with demand, the risk of potential contamination of stored water with pathogens from wildlife, potential negative effects on crop yields due to higher salinity, potential health concerns associated with contaminants, and public perception of use on food crops (91). Therefore, other actions should also be taken into consideration, such as monitoring pathogens and chemicals, optimization of treatments, assessment of treatment performance, reliability of treatments, etc.

Waste Reduction

By-product Applications

A great quantity of food waste and by-products are generated in many food processing sectors; a few examples include seafood processing (e.g., skin, bones), dairy processing (e.g., whey, curd), vegetable processing (e.g., seeds, skins, shells) and alcohol processing [e.g., brewers' spent grain (BSG), distillers' grains, pomace]. Many of these wastes contain valuable nutrients, such as polysaccharides, vitamins, minerals, fibers, and bioactive compounds such as flavonoids, lycopene, and other carotenoids, which are functional compounds (25) (**Figure 5**).

Effective utilization of wastes and by-product materials from the meat and poultry industries are of special interest due to high protein and amino acid levels, and high sales prices for these coproducts. High contents of proteins and iron within the blood and other coproducts makes them important edible by-products, which can be used to produce blood sausages, blood pudding, biscuits, and bread in Europe and other regions, as well as blood curd, blood cake, and blood pudding in parts of Asia. Other non-food applications are fertilizer, feedstuff ingredients (e.g., blood meal, meat, and bone meal) and binders. Due to the high foaming capacity of blood plasma, it can be utilized as an alternative for egg whites in baked products (92). Gelatin obtained from animal skins and hides is commonly used in different food and pharmaceutical products, such as meat products (as an emulsifier), ice cream, and other frozen foods (as stabilizers), medicated tablets and pastilles (as binding and compounding agents), and coverings of capsules (25).

Whey is an important by-product of the dairy industry, and contains several valuable constituents, such as proteins (e.g., α-lactalbumin, β-lactoglobulin, and immunoglobulin). In dry form, whey is commonly used in confectionery products, bakery products, and health and sport supplements due to high nutritional (including high amount of essential amino acids) and functional properties (e.g., gelation, foaming, and emulsifying properties) (93). Curd obtained from coagulating milk during curdling processes can be used in probiotic functional foods (25).

Bran is a major by-product of the grain industry, is a significant source of dietary fiber, and is added to various food materials, such as bread, cakes, noodles, pasta, and ice creams. Rice bran has been shown to improve functional and textural properties without altering flavor (94). Wheat bran is commonly used as animal feed. Wheat germ is also a grain byproduct, and can be used in various foods and other products, such as insect biological control agents, pharmaceuticals, and cosmetics (95).

Brewers' spent grain (BSG) is the main by-product of the beer brewing industry and is a source of cellulose and other polysaccharides, in addition to proteins. There are several applications for BSG, such as animal feeds (96), value-added chemicals (e.g., xylitol and lactic acid) (97–99), cultivation of microorganisms such as *Bifidobacterium adolescentis*, *Lactobacillus* sp. (100), and metal adsorption and immobilization materials for Cu ions (101).

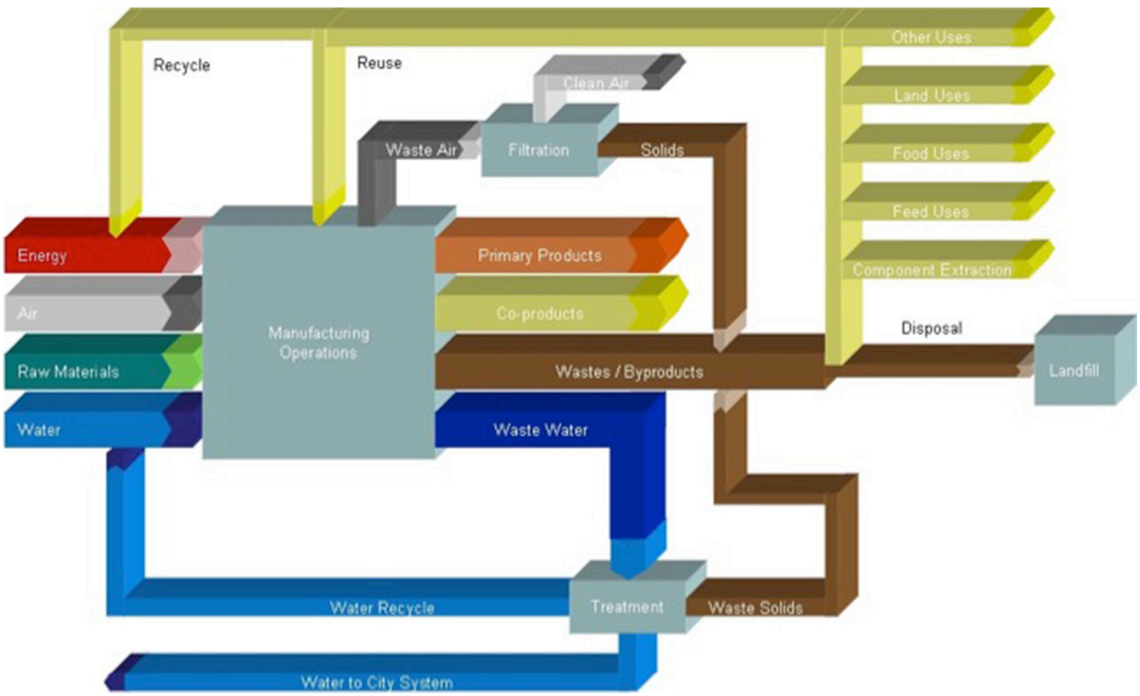

FIGURE 5 | Multiple pathways exist for utilizing waste streams as sources of energy or byproduct applications.

Due to various fruits and vegetables and the broad range of processes, there is a wide range of wastes obtained from fruit and vegetable processing (102). Moreover, depending on plant species, variety, and tissues, several nutritious compounds could be used in different products. Fruit and vegetable by-products offer great potential as a source of additives including antioxidants (e.g., vitamin C), antimicrobials (e.g., phenolic extract), colorants (e.g., anthocyanins), flavorings (e.g., essential oils such as terpenes), and thickening agents (103). Agro-industrial by-products are also reported to be a source of dietary fibers, which are used in the food, cosmetic and pharmaceutical industries (104). Additionally, several fruit by-products such as pineapple waste, grape pomace, and citrus waste could be used to generate ethanol (26), which will be explained in the following section.

Energy Generation From Food Waste

In recent years, food waste has become considered to be an untapped resource with much potential for the production of bio-based energy. Energy generation from food waste can be an option to pursue since this approach results not only in lowering the environmental burden of waste disposal, but also in providing energy to the plant, or it can be sold back to the energy grid. The two primary ways for converting food waste to energy include a biological approach (i.e., anaerobic digestion or fermentation) and a thermochemical approach (e.g., gasification, pyrolysis) (26).

Biogas is generated during anaerobic digestion (AD) of organic wastes, and consists mainly of CH_4 and CO_2, with trace amounts of other gases [e.g., nitrogen (N_2), oxygen (O_2), and hydrogen sulfide (H_2S)] (105). Murphy et al. (106) demonstrated that 1 m^3 of biogas from AD is equivalent to ∼21 MJ of energy, which can produce ∼2 kW h of electricity, assuming 35% conversion efficiency. Key challenges to AD include long process times required for microbial action (∼20–40 days), as well as high free ammonia (NH_3) content (released from the degradation of nitrogen-rich protein compounds), as well as high capital and operations costs (107, 108).

Ethanol production by fermentation of food waste is the other biological approach for converting food waste to energy. The most common microorganism used for this process is *S. cerevisiae*; however, other microorganisms have also been studied, such as *Zymomonas mobilis* and *Pichia rhodanensis* (109, 110). The drawback of *S. cerevisiae* is that it can only use hexose sugars/glucose as a substrate (111), but the other microorganisms can utilize pentose sugars (26). It has also been suggested that waste materials containing high amounts of carbon (e.g., brewery wastes, bran, potato chip waste, etc.) can be good substrates for ethanol production (112).

In terms of conversion of food waste to energy via thermal or thermochemical approaches, there are several methods, such as incineration, pyrolysis, gasification, and hydrothermal oxidation. During incineration, combustion results in heat and energy production from the food waste, which can then be used for operating steam turbines for energy generation, or in heat exchangers for heating up liquid process streams (113, 114). Although incineration can decrease solid waste volume by up to 80–85%, this method is not completely accepted by some countries, and it may even be banned in some countries due to air pollution and toxic air emissions (115).

Pyrolysis is carried out in the absence of oxygen at the temperatures between 250 and 750°C, which then generates bio-oil, syngas ($CO + H_2$), and biochar (i.e., residual devolatilized solid waste). Gasification is related to pyrolysis, and it also produces a combustible gas mixture (containing CO, CH_4, N_2, H_2, and CO_2); but instead of a complete lack of oxygen, the process uses a low content of oxygen, and thus partially oxidizes the food waste at high temperatures (800–900°C). The gas that is produced can be used in engines, and further processing can result in various chemicals (e.g., methanol) (26, 116). Ahmed and Gupta (117) conducted an investigation to compare the performance of pyrolysis to gasification for different properties such as syngas flow rate, output power, and total energy yield; they concluded that gasification was more efficient based on the evaluated criteria, however the gasification process required a longer processing time compared to pyrolysis.

Another thermal conversion technology is hydrothermal carbonization, in which food waste is converted to an energy-rich resource under autogenous pressures, and temperatures ranged from 180 to 350°C. This is a wet process, and offers several advantages, such as lower energy consumption, high waste utilization rates, no odors, relatively short process times (only a few hours), and microorganism destruction due to high processing temperatures (118, 119). Various food waste materials have been examined as substances, including fish meat (120), BSG (121), sweet corn (122), olive pomace (123), peanut shell (124), and grape seed (125).

CONCLUDING REMARKS AND FUTURE DIRECTIONS

The food processing industry consumes large quantities of energy and water. Due to increasing pressure to become more efficient, reduce costs, and reduce environmental impacts, many food processors are implementing technologies to achieve these aims. Energy efficiency has been proven to be greatly improved by replacing current energy- and water-intensive processes with novel, more efficient techniques, such as non-thermal processing. There are many approaches for more efficient water use, including various recycling and reconditioning treatments. Additionally, developing new applications for by-products as well as producing energy from various food wastes can reduce waste and pollution issues. Basic initiatives greatly improve the water efficiency (e.g., install a condensate re-use system, raising staff awareness about proper maintenance and water usage). These trends will continue for the foreseeable future, but their implementation will ultimately be driven by the economics of designing, building, and operating these new unit operations. For additional perspectives, opportunities, and information, the reader is referred to other papers that have been published in this Research Topic.

AUTHOR CONTRIBUTIONS

NN and KR searched for and reviewed the literature. NN drafted the paper. KR edited the paper and constructed the figures.

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