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Review

Combining the Water–Energy–Food and Food Waste–Food Loss–Food Security Nexuses to Reduce Resource Waste

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Abstract: The availability of water, energy and food plays a key role in meeting the basic needs of the world population and allowing them to achieve prosperity and supports the UN's sustainable development goals (SDGs). These three fundamental resources are closely interrelated, with their deep interdependencies reflected in various concepts of the **'water–energy–food nexus'** (W–E–F). One-third of the total food produced globally results in food loss and waste (FL and FW), which also means the waste of resources used for their production, mainly energy and water. We thus propose a fusion of the W–E–F nexus and the **FS–FW–FL nexus** to achieve a better correlation between food production and food consumption in order to avoid additional negative effects. We explore the **research problem** of how the availability of water, energy and food resources can be improved by reducing FW and FL. The **objective** of this paper is to present an overview of opportunities to reduce the negative effects of FWL. The review paper is based on a comprehensive analysis of the literature, exploration of various (basic and extended) W–E–F models and their linkages with SDG and the entirety of the food supply chain from field to table. In addition to a literature analysis, we applied comparative methods, modeling, visualization and basic indicators of descriptive statistics. Although the amount of literature on this topic is growing, we found that systematic knowledge is still scarce, with each new study putting forth yet more new solutions. Although the data in various studies show somewhat different results, we conclude that reducing FW and FL has a positive, harmonizing effect on the W–E–F nexus.

Keywords: nexus W–E–F; nexus FW–FL–FS; food waste; food losses; food security; resource efficient technologies

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1. Introduction

The resources of water and energy are becoming increasingly sensitive. Water scarcity has been identified as a pervasive threat to global society and economy with an estimated two-thirds of the global population already experiencing its severe effects [1]. The depletion of fossil energy resources and the rising demand for energy coupled with the high environmental costs of energy production make energy issues similarly dire. Additionally, societies in many countries are experiencing food shortages for various reasons such as overpopulation, drought or poverty, causing hunger and malnutrition. Political, economic and natural crises (e.g., droughts, floods, hurricanes) as well as the changing climate and growing population aggravate this situation even further. At the same time, however, huge amounts of food are wasted in all countries and at various stages of the food chain, straining the sensitive water and energy resources. It is estimated that, globally, one-third of the total food production results in food waste (FW) and food losses (FL) [2]. This has prompted various mitigation policies at regional, state and international levels, such as the objective to reduce 50% of food loss and waste at the retail and consumer levels by 2030, along with an unspecified reduction at earlier supply chain stages, set by the UN sustainable development goals (target 12.3.) [3].

Food wastage can be categorized as food waste (FW) and food loss (FL), where FW is defined as inedible food and FL as food appropriate for human consumption that is discarded or left to spoil, regardless of the cause [4]. The waste and loss of food occur at all stages of the food supply chain, including during transportation, from agricultural food production, harvesting, storage and food processing into products to wholesale, retail, restaurant and institutional food service and household use. While systematic data on FWL and its environmental impact at each stage of the food supply chain are not available, it is estimated that, worldwide, 413 MT of food is wasted at the agricultural production stage, 293 MT in postharvest handling and storage, 148 MT in processing, 161 MT in distribution and 280 MT in consumption [5]. For comparison, in the EU, 39% of all food loss is estimated to occur in food manufacturing [6]. Another important category to consider in the context of FWL is food security (FS), which refers to the confidence in the food production system, supply chain management, availability, continuity and sufficiency for the consumer and industry now and in the future [7]. Together with FW and FL, food security builds a FW–FL–FS nexus.

Food waste and loss in the early stages of the supply chain can be reduced by exchanging resource-intensive products for more sustainable foods. In developed countries, consumers have a wide range of food products to choose from, offered by the food industry. They prefer to buy products that are already partially prepared for consumption (convenience foods) rather than those that require lengthy pre-processing and often choose novelty over rational products [8]. A rich market with a constant supply of novelty and innovation opposes a traditional and saturated market that lacks freshness. Today, many consumers are fascinated by different eating habits and food products with new sensory and organoleptic characteristics. This is due to, among other things, the increasing mobility of societies and the acceleration of technological development. This results in changing values and the emergence of quite distinct generational differences every ten years or so. Successive generations, BB, X, Y (so-called millennials) and the current generation Z, differ in their approach to food and nutrition due to biophysical, cultural and social dimensions [9]. Some are looking for products which are easy to prepare, others for foods with new taste or nutritional value and still others for foods with enhanced health properties. Additionally, over the past 30 years or so, consumers have been becoming increasingly concerned with sustainability and climate change, which has given rise to green consumerism with preferences for ecological and/or sustainable products [10]. The food industry is, on the one hand, responding to these preferences by bringing desirable products to the market. On the other hand, it is actively seeking higher profits and market niches, e.g., by launching its own novel (cost and/or resource-efficient) offers.

The above-mentioned elements are directly or indirectly linked to the W–E–F (water–energy–food) nexus, a concept that is still developing and expanding its boundaries. The term W–E–F nexus rose to prominence in the past decade due to the speech of the Secretary General of the United Nations, Ban-Ki Moon, during World Water Day in March 2011. He noted that the interconnections between water, energy and food are among the greatest challenges that mankind faces. The term nexus means "to connect" and conveys interactions between two or more elements and their dependencies or interdependencies. In the first definitions of the term 'nexus' in the Oxford Dictionary [11], the nexus between industry and political power and a nexus of interests, including, lately, "interactions and interconnections among different sectors (or subsystems) considering food, energy and water", are mentioned.

The aim of this paper is to explore how the imbalance within the W–E–F nexus [12–14] can be remedied by combining it with the FW–FL–FS nexus and reducing FW and FL. For this purpose, we describe the water–energy–food nexus (Section 1) and food waste–food loss–food security nexus (Section 2) and explore the high input of water and energy in the food supply chain from field to fork (Section 3), highlighting the most resource-intensive areas in which these inputs could be reduced.

2. Water–Energy–Food Nexus

More than 1 billion people nowadays are undernourished, another 1 billion have no safe water and 1.5 billion have no source of electricity [15]. We are also becoming increasingly aware from painful experiences that "(w)ater, energy and food are inextricably linked" [16]. Access to these resources and their effective management underpin development progress and are prominent in the UN SDGs, among other activities. Projections show that the world economy will need more electricity in 2030 compared to in 2007 [17]. At the same time, global water demand could rise by between 35% and 60% between 2000 and 2025 and double by 2050 [18]. In addition, to meet projected demand, cereal production will have to undergo a 50% increase, and meat production an 85% increase, between 2000 and 2030 [19]. The most important factor in choosing the right tool for addressing the resource nexus is the clear identification of the problem at hand, which interlinkages of resources are important, the data needed to assess their availability and in which part of the world the problem occurs.

On the other hand, however, the linkages between freshwater supply and energy production and the extraction and processing of minerals and energy have not been given due attention. Moreover, environmental challenges and economic fluctuations make these relationships even more uncertain and unpredictable, especially given the changing political dynamics of the international system, with the rise of powers such as China, India and Brazil. Understanding and quantifying these resource linkages can also present opportunities such as productivity gains, substitution, reuse and recycling and reduced consumption, to name a few, while minimizing the risks associated with resource management [20]. However, not all modeling tools have the capabilities to deal with all kinds of problems anywhere in the world [21].

Additionally, the approach taken and the decisions made in the policy-making process reflect the perspective of the policy maker, meaning that if a water perspective is taken, food and energy are the users of the resource, and, from a food perspective, energy and water are the inputs, etc. As noted by Lee and Ellinas, "anticipated bottlenecks and constraints in energy, water and other key natural resources and infrastructure bring new political and economic challenges, as well as new and difficult-to-manage instabilities" [22]. Making policies for one sector may temporarily improve performance in that sector of the economy, but this is highly unlikely to be sustainable over the long term. A holistic approach can lead to a more optimal allocation of resources, improved economic efficiency, reduced environmental and health impacts and improved conditions for economic development.

W–E–F Nexus Models

Due to the inextricable links between the systems of water, energy and food management and their external resources and biotic environment, the sustainability triangle in the W–E–F nexus is evolving to include more dimensions, creating larger models such as the water–energy–land–food [23], water–energy–climate–food [24] or ecosystems–water–food–energy [25] frameworks. This creates challenges for integrating and optimizing the components of this multi-centric nexus, as examined and evaluated by Leck et al. [12] and other scholars [22–24]. A 'simple' nexus relationship between water, energy and food is often represented as a triangle, with the respective resource subsystems connected by bidirectional lines or arrows to describe the bilateral interactions between them. The figure is also sometimes drawn as a circle depicting interactions with the natural, political and climatic environments (Figure 1).

This bidirectionality of interactions between the subsystems in the W–E–F nexus model can be described as follows: the relationship between W–E is defined as "availability and use of water for energy production" (green and blue water); the inverse relationship E–W as the "impact of energy production on water quantity and quality"; the relationship between F–W as the "impact on water quantity (changes in run-off) and quality (e.g., salination, eutrophication)"; the inverse relationship W–F as "availability and use of water for food production, (green and blue water)"; the relationship F–E as the "direct impact from food production to energy use and energy security"; and E–F is described as "the direct impact of energy production on food security including agriculture and fisheries" [26].

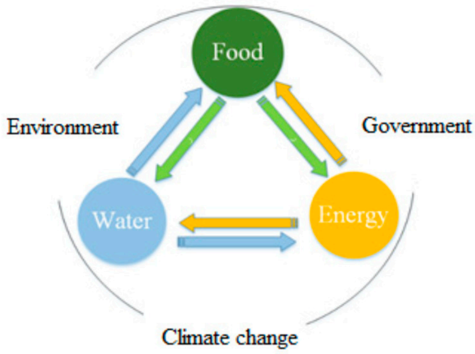

Figure 1. Nexus W–E–F. Source: [13].

According to Albrecht et al. [27], "while the W-E-F nexus offers a promising conceptual approach, the use of W-E-F nexus methods to systematically evaluate water, energy, and food interlinkages or support development of socially and politically relevant policies has been limited". In the cited review, the authors showed that the survey methods were largely non-specific, with a high prevalence of qualitative methods limited to a small number of scientific disciplines, making inference difficult and diminishing usefulness for practice. After all, it is expected that a nexus should organize and explain the relationships that exist between resources and systems in a systematic way and through quantitative methods [28]. In another publication, the authors examined the influence of qualitative and quantitative factors related to the environment, health, economics and social relations that may be different in different geographic and political environments [29]. The study concluded that the W–E–F nexus can be an effective vehicle for advancing water and sustainability issues and recommends further research and demonstration projects to test the extent to which the W–E–F framework could be helpful in increasing understanding and collaborative governance approaches.

In another publication [30], de Grenade et al. placed the W–E–F nexus between interacting social (human) and natural (physical) systems. Their review of recent literature indicated that publications generally include the natural environment, social-ecological systems and external conditions. In the above-mentioned paper, the authors wrote: " ... The concepts of environment, land, ecosystems, ecosystem services, and climate change play a structural role in these discussions, however the context of how these concepts are integrated, at what scales, for whom, and to what end varies widely. Furthermore, within nexus scholarship, consideration of social-ecological systems theory, resilience, and adaptive capacity remain largely unexplored". Based on their research and analysis, they proposed to extend the notion of the nexus to the broader environment, as shown in Figure 2. Bleischwitz et al. [31] used a pentagonal model (Figure 3) to present the W–E–F nexus with two elements attributed to SDG targets: materials and land.

A very sophisticated and complex W–E–F model was proposed by Biggs et al. [32] to conceptualize environmental livelihood security as " ... refer[ring] to the challenges of maintaining global food security and universal access to freshwater and energy to sustain livelihoods and promote inclusive economic growth, whilst sustaining key environmental systems functionality, particularly under variable climatic regimes ... ". This comprehensive model seeks to cover all types of water, energy and food resources on Earth and their interdependences. Biggs et al. presented a novel framework for incorporating livelihood dynamics into the W–E–F nexus which builds on its strength and livelihood approaches to explore and develop the concept of 'environmental livelihood security'. The authors argued that an integrated and holistic approach to measuring and achieving sustainable development outcomes in multi-scale systems is able to better inform development policies and programs.

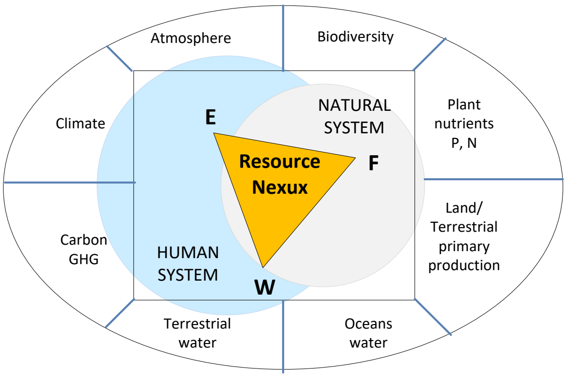

Figure 2. W–E–F nexus in environment. Source: own drawing inspired by de Grenade et al. [30].

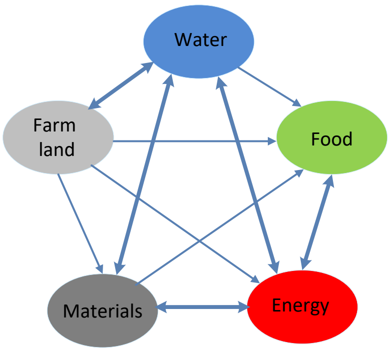

Figure 3. Five-element nexus: water, food and energy, with addition of farm land and materials. Thick arrows with two arrowheads indicate two-way interactions, and thin arrows indicate one-way interactions. SDG indicators have been omitted. Source: own depiction inspired by Bleischwitz et al. [31].

Other models in the literature seek to integrate physical, technical, social and economic components of the nexus in novel ways, e.g., in [33]. The introduction of the 'ecosystem' (see Figure 4) or 'waste' perspective in the middle of the W–E–F nexus points to the main sources of wastage: the complex production and consumption of food from field to table and water resources.

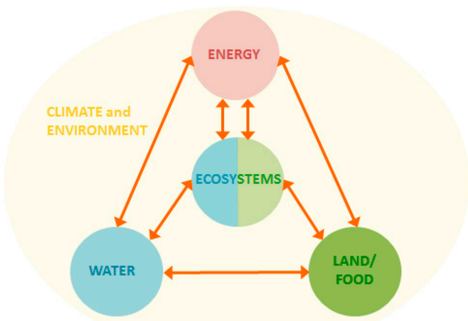

Figure 4. Typical W–E–F nexus enriched by the ecosystem category placed inside the W–E–F triangle. Source: [33].

The methodology presented by Santeramo et al. [33] was used to develop a series of nexus assessments of selected river transboundary basins in Europe. The objective was to identify trade-offs and impacts across sectors and countries and to propose possible policy measures and technical actions at national and transboundary levels to reduce intersectoral tensions. This was carried out jointly with policy makers and local experts. Such a method offered the opportunity to better involve key economic sectors, in particular, the energy and agriculture sectors, in the dialogue over transboundary water resource uses, protection and management. Similar studies are being carried out in other parts of the world. One of their objectives is to improve water allocation policies, which can help to reduce negative climate change and its impact on water and energy availability for agriculture. This is expected to affect surface water levels and, subsequently, produce better yields and more energy from hydroelectricity [34,35].

An interesting approach to the proposal to extend the traditional W–E–F nexus to include waste was presented by Bowen et al. [36]. This construction can be seen as an isosceles triangle with waste placed in its center or as an equilateral tetrahedron with waste on top of the pyramid. The relationship between W, E and F is bilateral. For example, the food sector supports the production of biofuels and biogas. The energy sector supports transportation and production of fertilizer and the food chain. The introduction of waste and losses into the nexus is very important and creative because it indicates the main sources of their creation: food and water.

In another proposal [37], which is more general, the nexus is described as an analytical tool or method to quantify the links among the nexus nodes, including various characteristics or properties of food, energy and water. Some examples are shown in Table 1.

Table 1. Other possible synonyms of W–E–F nexus.

Food	Energy	Water
Security	Security	Hardness
Availability	Supply on demand	Availability
Access	Physical availability	Quality (health)
Optimal water utilization	Satisfy on demand	Cost effectiveness

Source: own proposal.

Further theoretical reflections and research are necessary in the context of the dynamic changes in social, environmental and ecological systems and the implications that adaptive action has for resource-using sectors and the environment. A more holistic nexus framework enhances the ability to manage environmental interactions, human activities and policies in order to adapt to the uncertainties associated with global change, which have recently intensified. However, with the conceptualizations of the W–E–F nexus becoming increasingly complex and incorporating a plurality of various data, comprehensive quantitative analyses of dependencies and interactions grow more difficult. We found that most nexus analyses were conducted at regional or national levels, and their scope was highly dependent on the availability of data, national-level policy goals and metrics [38].

3. Food Loss–Food Waste–Food Security Nexus

The global demand for water, energy and food will be driven by the rapid population increase from 6.5 billion now [15] to more than 9 billion in 2050 and will be connected with changes relating to lifestyle, urbanization, deforestation, climate change and other things. Around 1.5 billion tonnes of food are currently wasted worldwide [2]. Similar data are quoted by other authors, e.g., Sun et al. [39]. Furthermore, "(f)ood losses and waste (FWL) cause unnecessary energy and water consumption along the food supply chain. However, little is known about the energy and water losses related to FWL". The authors did not leave this observation unanswered. Their research showed that the FWL of vegetables, meat, fruit and grains in the US is 27.8, 18.5, 17.4 and 7.0 million tonnes per year, respectively.

Food waste (FW) is defined by the High Level Panel of Experts (HELPE) as inedible food and food losses (FL) as food appropriate for human consumption that is discarded or left to spoil, regardless of the cause [18]. A methodology of food waste measurement was presented by Corrado et al. [19]. However, Chaboud et al. [21] indicated inconsistencies in the measurements of FW and FL, and Canali et al. [20] mentioned the causes of FW in Europe. Policy measures to contain loss and waste at different stages of the food production and supply chains are crucial to reducing their impacts on food security [40]. Therefore, identifying, assessing and managing the links between FL, FW and FS are promising research areas, and it is important for future W–E–F nexus research to consider the interrelationship between FWL and food security.

Reducing FL and FW also has great potential to minimize resource inputs, such as water and energy used in food production, which are de facto wasted along with food. It is an uncontested fact that food production and supply chains are highly resource intensive, especially if this intensive use of resources is directed toward the production and delivery of food which is then wasted. Reducing FWL means reducing the environmental impacts associated with food production and consumption and increasing food security. As FL and FW imply inefficient use of resources (i.e., water, energy, land, etc.) in the food production systems with a detrimental impact on the level of food security, policy measures to reduce FWL at different stages of agri-food production and food supply chains are key to reducing the impact on food security.

Water, energy and food security (FS) are closely interrelated, and considering the impact of FS on the aforementioned resources is crucial to achieving sustainable goals in future [41]. Considering the above-mentioned arguments, we propose including the FW–FL–FS nexus into future W–E–F nexus considerations, as combining both perspectives enables an increase in W–E–F nexus efficiency, lowering the resource inputs and including a more holistic approach to the food production aspect of the W–E–F nexus (see Figure 5).

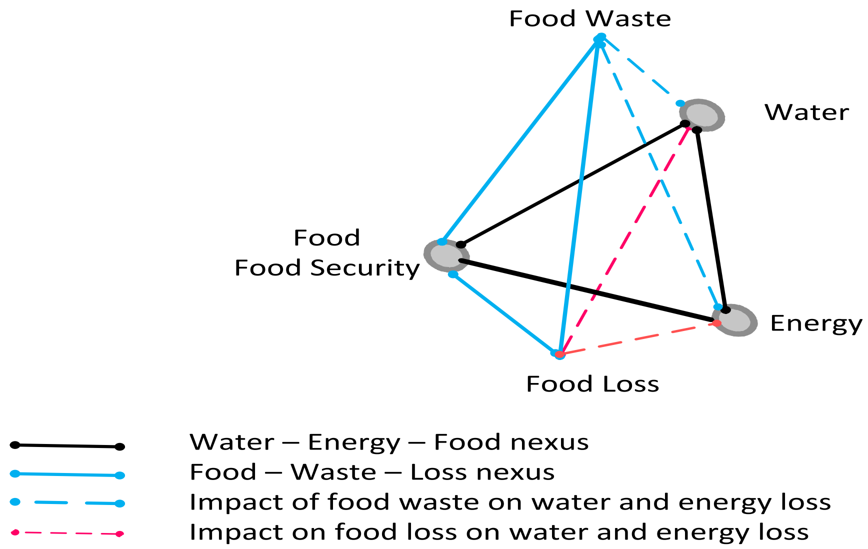

Figure 5. Relationship between W–E–F and FL–FW–FS nexuses. Source: own model.

As showed above, the W–E–F nexus (in black) and FL–FW–FS nexus (in blue) meet at the points F and FS. The dashed lines in red show the relationship between FL, E and W, while the blue lines indicate the impact of FW on water and energy resources. In this way, the interactions between FWL, FS, W and E are fully encompassed, and their inextricable nature is properly reflected.

Given the multidisciplinary nature of the issue, researchers from different research areas (e.g., agricultural sciences, agricultural economics, development economics, environmental sciences, engineering) can contribute to understanding the impact of FWLs on food security, water and energy use and deepen the understanding of all the aspects emerging from a holistic analysis, as presented in Figure 5. The findings of our literature review suggest that exploration of the synergies between different supply chains, insights into more efficient resource management based on the principles of circular and green economy approaches (i.e., reduce, reuse, recycle) and more environmentally friendly agriculture methods and crops would advance W–E–F and FW–FL–FS nexus research even further. The challenge of future research will be, thus, to provide insight and find solutions that are "more oriented towards the protection of the environment, the preservation of the natural resources, in order to facilitate the emergence of strategies able to promote the circular economy and to reduce food wastage" [42]. In Table 2, we present an overview of measures to reduce FWL suggested in literature.

Table 2. Actions suggested to reduce FW and FL. Source: own elaboration based on the literature analysis.

During Processing	Support to Growers	Support to Consumers
identification of causes of FWL	transforming perishable raw materials into shelf-stable products	extension of the shelf life through packaging and processing innovation
training courses for personnel (at all stages of the supply chains)	positioning factories near fields	introduction of clear date labels
optimization of the production	improve storage, cold chain, transportation	improve storage, freezing, defrosting and preparation instructions
transformation of food loss and by-products into fertilizer or compost	redirection through different channels (e.g., food banks, markets)	supply of a variety of portion sizes
transformation of food loss and by-products into renewable energy	redirection to feed animals and to industrial use	provision of information on packaging and labelling innovations that help to prevent food spoilage

4. Energy and Water Use in the Food Industry

Food waste and losses (FWL) cause unnecessary energy and water consumption along the food supply chain. Sun et al. [39] showed that water loss related to the FWL of the four food sectors is 372 billion m^3 per year, of which 75% occurs in the meat sector due to its high virtual water consumption. The total CO_2 emissions (indicator of energy losses) of the four food sectors is 620 million tonnes per year, with 85% in the meat sector. In addition, FWL has a higher positive correlation with energy use than with water use. Coudard et al. [14] stated that 344 Mt of global consumer food waste is produced annually, and approximately 4 trillion MJ of energy and 82 Bm^3 of water are lost. Quantification of FWL impacts on the W–E–F nexus indicates the importance of reducing FWL not only for food security but also for energy and water savings.

The food industry uses numerous energy- and/or water-intensive technologies. Many research papers showcase the best cases and practical applications of energy and water reduction measures. For example, FAO [40] published examples of energy conservation in various forms in technical and social and direct and indirect actions on farms, as shown in Table 3. The food industry is also responsible for a considerable amount of greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions.

Table 3. Examples of energy efficiency improvements through direct or indirect technical and social interventions in the food sector.

	Energy Improvement Examples
Directly on the farm	Fuel-efficient engines, maintenance, precise water applications. Precision farming for fertilizers. Controlled building environments. Heat management of greenhouses
Off-farm	Better lighting and heat processes. Insulation of cool stores. Minimizing packaging of food. Improving efficiency of cooking devices
Indirectly on the farm	Fewer input-demanding crop varieties and animal breeds, agro-ecological farming practices. Reducing water demand and losses. Energy efficient fertilizer and machinery manufacture
Indirectly outside the farm Farm	Reducing food losses at all stages of food chain. Matching food supply with demand. Changing diets from animal products. Lowering obesity levels. Labelling of food products

Source: [40] FAO (2011), "Energy-smart Food for People and Climate", Issue paper, Rome, FAO.

4.1. Energy

The food sector consumes approx. 200 EJ per year globally and accounts for approx. 30% of global energy consumption [43]. Energy is needed at every level of the food supply chain, including during the production of agricultural inputs, agricultural production in the field, animal production, harvesting, food processing, distribution, wholesale, retail, marketing and preparation for consumption. Among the total food production costs, energy-related costs are estimated to make up between 20% and 50% [44]. Moreover, the food industry represents a relatively high percentage (approximately 12%) of the total electricity consumed in the industrial sector in the EU [45]. Energy sources and consumption by food sectors in EU are shown in Table 4.

Table 4. Energy consumption in food industry and agriculture with forestry in 27 European countries in 2018.

Sector	Energy Sources (ktoe) *						
	1	**2**	**3**	**4**	**5**	**6**	**7**
A	27559	1410	1541	12760	1083	1280	9457
B	27250	951	15449	3322	2841	251	4372
C	939682	22536	345072	200766	98902	46200	215972

A—Food, beverage, B—Agriculture, forestry, C—Final energy consumption in EU 27. 1—Total, 2—solid, fossil fuels, 3—oil and petroleum, 4—natural gas, 5—renewables and biofuels, 6—heat, 7—electricity; * the energy balance expresses all forms of energy in a common accounting unit "toe" (tonnes of oil equivalent) as ktoe (thousands toe) or Mtoe (millions toe). Source: own elaboration based on p. 24, [45].

Globally, primary agriculture consumes only approx. 20% of all energy inputs in the food supply chain, whilst food processing, including transport, uses around 40% and thereby significantly contributes to global energy consumption along agricultural value chains [40]. Other authors gave the following energy breakdown for energy use in food production: 37%—retail, 42%—production and transport, 2%—fish farming, 6%—animal husbandry and 13%—agriculture [46]. The consumption of energy differs also across crops and products; while vegetable and melon crops are generally found amongst the most energy-consuming crops [47], instant coffee, milk powder, French fries, crisps and bread are found among the most energy intensive food products [15]. The data differ, however, for particular countries and production methods, with specific factors such as fertilizers, packaging or even sanitation and production standards accounting for a significant part of the total energy input per crop or product.

However, the energy in the food sector is not always used efficiently. In food processing, the main consumer of energy inputs in the food industry, this mainly applies to heating, one of the main sources of energy consumption in this sector. Due to inherent constraints in the heating processes, a portion of heat is wasted. However, heat recovery is possible by power generation technologies. In addition, novel applications and thermodynamic cycles, which use low-grade heat or renewable energy (RE) for heating or cooling processes, can be applied by the food industry [41]. Heat pumps can recover heat directly from certain processes, such as milk pasteurization. Other processes, which require higher temperatures, can use pumps to upgrade low-quality waste heat to 150 °C. Results show that heat pumps can recover up to 40% of waste heat and lower energy costs by 20%. Novel refrigeration cycles suitable for small plants, supported by absorption–desorption or absorption systems, are available as well. In some processes, the food industry can use non-thermal methods such as irradiation, pulsed electric fields, high pressure or membrane processing. Non-thermal methods can save up to 50% of heat compared to the conventional method [48]. Among novel, low-energy methods of food sterilization, such as infrared, microwave, ohmic and radio frequency, the last is the most cost effective [49].

4.2. Water

According to the OECD, it takes 2000 to 5000 L of water to produce a daily ration of food for one person [50]. Water consumption by products can be measured by water footprint (WF) indicator, which makes it possible to measure freshwater's direct and indirect use throughout the food supply chain. Similar to energy, water inputs related to food occur repeatedly at different stages of production, including in agricultural production, harvesting, processing, packaging, etc.

One-third of freshwater consumed in global food production is effectively wasted since the food produced with this water is never consumed, with an estimated 7.1% of the freshwater planetary boundary linked to FWL [51]. However, the WP of produce and products differs by country, production technology and diet. Marston et al. [52] gave an overview of study results for FWL-attributed water waste in their review article, stating that the USA has "the highest blue water footprint associated with FLW per capita (. . .) and, along with India and China, the largest volume of blue water attributed to FLW". However, the authors urged caution as "(m)any studies ignore, or greatly simplify, the complex supply chains that connect the locations of food production, processing, consumption, and waste (. . .), which has implications on estimated water footprints and contributions to water scarcity of FLW".

Across the FSC, the largest water inputs are related to irrigation and, thus, are estimated to occur in primary agriculture, with comparatively small inputs attributed to other stages of the value chain [53]. Many studies across regions reported the largest water use and impacts of FLW occurring mostly during the production stage and at the consumer level. A recent study by Read et al. [54] confirmed that, amongst all food supply chain stages, reducing household consumption waste could avert the most water consumption.

Among produce groups, data vary significantly across countries and are strongly diet-related; while meat and dairy are at the forefront in high-income countries, with the largest FWL-associated water footprint, in countries with mostly vegetarian consumption, crops such as sugarcane, rice, wheat and potatoes take the lead. In the USA, fresh vegetables have been found to require the largest amount of water from field to fork, followed by a category including nuts, seeds, other snacks and ready-to-eat or ready-to-heat foods [55]. An online resource at OurWorldInData gives a comprehensive overview on food-associated water issues, stating that most freshwater withdrawals per kilogram of food product occur in cheese, nuts and prawns production [56].

5. Conclusions

The paper presented results of a comprehensive literature review on the W–E–F nexus and the different interpretations and explanations by experts regarding partial connections and bilateral effects within this nexus, e.g., W–E, E–W, E–F, F–E, F–W and W–F. We also considered several publications in which the W–E–F nexus was expanded to include impacts of external factors, e.g., environmental (water, atmosphere, climate, carbon emission, terrestrial water), human and ecological factors (biodiversity, phosphorus and nitrogen as plant nutrients, ocean water, land primary production). In some publications, the triangular nexus was developed into a pentagonal or spatial (three-dimensional) model to better explain the relationships between its elements and the SDG targets.

The analysis of the collected literature shows that since the beginning of the 21st century, the problem of water, energy and food resource management has been increasingly recognized among representatives of science, the economic sphere and the governments of individual countries. The resources that make up the W–E–F nexus are usually represented in scientific publications as an equilateral triangle, suggesting balance and harmony between them, which is, in fact, not yet achieved, despite many efforts towards compatibility and coordination on a global scale. Moreover, our analysis shows that the W–E–F nexus has not yet received corresponding consideration in the food industry, although this production sector is particularly heavily dependent on water, fossil fuels and electricity. With the increasing world population, food demand is expected to grow in the coming decades.

Therefore, developing energy and water efficient strategies for this particular industrial sector is crucial [57,58]. At the same time, the global economy is advocating de-carbonization, circular economy and greater access to food. These developments are closely linked to the imbalance in the W–E–F nexus and prompted us to pay special attention to solutions offered for more sustainable food production.

As our literature review shows, reducing FL and FW can decidedly lessen the environmental impact by producers and consumers. However, this requires appropriate education programs and food policies at macro and micro levels. Other relevant actions for resource conservation are presented in Table 2 (p. 14).

Due to the vast potential of water and energy savings in the food production, we suggest combining the W–E–waste nexus with the FL–FW–FS nexus, as shown in Figure 5, which enables a more prominent consideration of FL and FW in the analysis of energy and water losses and is a novel contribution to the literature on the subject. We also argue that, among the principles of sustainability, we must choose one of two: strong or sensitive [59], with strong assuming that natural and economic capital are not substitutable but complementary, and the sensitive principle assuming that both capitals can be substituted (although to a limited extent).

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