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Review

Conceptualisation of an Ecodesign Framework for Sustainable Food Product Development across the Supply Chain

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Abstract: As the world population grows, the pressure to intensify an unsustainable food production system increases. At the same time, one-third of all the food produced is lost or wasted along the value chains. Therefore, it is crucial to develop methods to increase food production while decreasing resource usage and minimising the environmental impact. Ecodesign concepts have already been implemented in various sectors, reducing the environmental impact of products. However, published work has yet to analyse the potential of ecodesign for food production across the value chain. This review assesses the existing literature on ecodesign principles and proposes a conceptual framework of strategies to be applied to current food chains, addressing the challenges posed by current agrifood systems. We suggest that the relevant ecodesign principles fall into three main categories depending on the supply chain stage: "design for sustainable sourcing (DfSS)", "design for optimised resource use (DfORU)", and "design for end-of-life optimisation (DfEO)." Applying this framework across the supply chain could significantly reduce the environmental impact of food production and indirectly contribute to dietary change.

Keywords: circular economy; ecodesign; recycling; sustainable product development

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1. Introduction

The current food system is unsustainable, producing between 20 and 35% of the Earth's Global Greenhouse Gas Emissions (GHGs) [1–4], translating to around 13.7 billion metric tons of CO_2 eq. [5]. Together with these emissions, food production is also responsible for: (1) consuming 70–90% of the world's freshwater use [3,5–7]; (2) occupying around 40% of arable land [6]; (3) consuming around 30% of the world's total energy [8]; and (4) being responsible for most of the biodiversity loss over the years [9]. With this, some authors set specific constraints for agrifood system development to guarantee healthy and sustainable diets [6].

The limited amount of natural resources available for food is one of the most pressing subjects nowadays due to the increase in population [3,10,11], projected to reach 9 billion by 2050, especially in the developing world (United Nations, 2019a). In addition to this, around one-third of the food produced—approximately 1.3 billion tons [12,13]—is lost or wasted in a year. This type of waste generates about 8% of GHGs [14–16]. This current situation is unsustainable, so it is vital to find new ways to produce food, reduce waste, and provide the necessary nutrients to the population [6,7,11]. Processing food products is one option to reduce waste as such products appear to have a lower wastage percentage than fresh food and seafood [17]. In 1987, the World Commission on Environment and Development defined the importance of sustainability, its objectives, and its key elements. The elements included having sufficient energy for all human needs, minimising the waste of primary resources, protecting public health and the environment, and even avoiding localised forms of pollution [18]. Promoting sustainability is crucial not only to reduce the impact of production (improve efficiency) but also to find methods for the "green design" of products [19].

Over the years, several important concepts have emerged, tackling the sustainability of different products or services. In particular, European governments and industries have broadly accepted the circular economy concept. In 2015, the European Commission adopted the Circular Economy package, highlighting an ecodesign Directive as one of the most suitable legislative tools for achieving several circular economy objectives. Ecodesign can be broadly defined as incorporating environmental aspects into the design and development of products, improving the environmental performance of products throughout their life cycle [20]. It is seen as a preventive approach to optimise and decrease the environmental footprint of products while not hindering their final use [20]. It can potentially translate the circular economy principles into specific product material efficiency requirements, a crucial factor in the Community Strategy on Integrated Product Policy [21].

Ecodesign grew and developed in different fields, such as architecture, electronics, process engineering, and pharmaceutical packaging [22–25]. However, ecodesign concepts involving the efficient (re)utilisation of food biomass are currently not available, and there is a lack of information on how ecodesign can be used to develop viable ecological concepts applicable to food products.

Bearing in mind the current need to devise solutions that can diminish the environmental footprint of current food systems, this work aims to: (i) identify the ecodesign conceptual approaches that can be applied to the specifics of perishable products of the agrifood system; (ii) establish a conceptual ecodesign framework applicable for practical and theoretical testing and possible novel product development, and, finally, (iii) highlight the necessary legislative framework to accommodate this strategy. Perishable food products receive the most focus in food loss and waste reduction efforts due to their significant contribution to the overall percentage [26].

2. Ecodesign Principles

Ecodesign, also known as Green Design, Sustainable Design, Environmental Design, or Design for Environment (DFE) [22,24,27,28], is not new. Although the term ecodesign suggests that sustainability only concerns the design of products, it is essential to note that focusing on the design phase of a product has implications for its entire life cycle: manufacturing, use, and disposability. This approach involves using processes that minimise the consumption of natural resources, enhance product durability, reduce weight and pollution, and encourage recycling and reuse of operable product parts [22,29,30]. By optimising the design process, ecodesign can reduce environmental impacts throughout a product's life cycle, from sourcing raw materials to their disposal or reuse [23,27]. Other improvements have been suggested and involve enhancing durability; saving energy, reducing products' weight; reducing pollution; recycling materials; and others [24,31]. For example, it has been applied successfully in other areas, such as electronics, which are currently built to be easily disassembled and repaired [22] or decrease the environmental footprint of packaging [29].

As Stevels [32] describes, there was a "start-up" period in the early nineties when many manuals were developed to help follow the concept. The developed frameworks usually encompass recycling, remanufacturing, reuse, and Life Cycle Assessment (LCA) during the design phases of the product [27,28].

The ecodesign concept can be broken down into different categories according to different authors [27,31,33,34] (Table 1), whilst others [30,35] integrated ecodesign into the hierarchy of food waste treatment [36].

Table 1. Systematisation of different ecodesign strategies meant increasing product and service sustainability. These strategies are collected from different application areas of this concept and are not necessarily related to food design. Various literature sources give various titles to ecodesign goals with the same objectives, making it possible to draw similarities between them and group them. Within the context of food design, "hazardous substances" can be interpreted as "toxic" or "harmful" because, when referring to design for reuse (reprocessing of food products), there may be a generation of toxic substances—e.g., migration of microplastics [37] or other substances [38] from the packaging to the product.

Ecodesign Strategy	General Principles	Reference
Design for sustainable sourcing	• Source virgin raw materials or renewable raw materials from sustainably managed production processes; • Utilise recycled materials as secondary raw materials.	[31,39]
Design for optimised resource/optimisation/LCA	• Avoid unnecessary material use, and reduce the amount of material used; • Chose recycled and recyclable materials over non-recyclable materials; • Use materials that do not contain hazardous substances; • Optimise the process for lower resource consumption as well as environmental impact of by-products; • Manufacture without the production of hazardous compounds or without incorporating them in the product; • Use clean technologies (renewable energies).	[27,31,33,39]
Design for environmentally sound and safe use phase/for energy efficiency	• Minimise the exposure to hazardous substances during utilisation of the product; • Minimise particle emissions during use; • Minimise the likelihood of littering; • Minimise product energy consumption.	[27,31,34]
Design for prolonged product use/disassembly/maintenance	• Easy disassembly of the product to ensure repair/substitute parts of the product rather than replacing the complete product; • Create durable products; • Maintenance of the product to avoid having to repair or substitute parts.	[27,31,34,39]
Design for reuse/recycling/recovery & material recycling	• Identification of product parts that can be reused the right way and parts that can be recycled; • Easy dismantling of products for recollecting and sorting out parts that are still reusable or recyclable; • Use of recyclable polymers and/or polymer blends using existing recycling infrastructure; • Elimination of hazardous substances or polymers.	[27,31,34,39]

2.1. *Ecodesign Tools Applicable to Food Products*

As seen in Table 1, specific ecodesign strategies are oriented toward the "cradle" part of production chains, aiming for the sustainable production of raw materials. Others concentrate on optimising and tuning every step of the product transformation along the chain. A few design strategies are oriented to deal with the "end-of-life" of a product, aiming for material restoration, reuse, or recycling. Prolonged durability (shelf-life in food products' case) is also beneficial. Therefore, we can aggregate them into three main strategies to define and deal with the ecodesign of food products: (1) sustainable sourcing; (2) optimisation along the supply chains; and (3) end-of-life optimisation. With these, tackling points that can be improved throughout the current food chains to minimise resource consumption and emissions may be possible.

From the strategies identified in Table 1, three main categories are more relevant to food system optimisation: (1) ecodesign for sustainable sourcing (DfSS), (2) ecodesign for optimised resource use (DfORU), and (3) ecodesign for end-of-life optimisation (DfEO). How these ecodesign strategies can help improve the environmental impact on food systems is discussed in detail in the sections below.

2.2. Framework for Ecodesign of Food Products

This review explores how ecodesign principles can be used to improve food production. A comprehensive framework for this would include eco-efficiency improvement throughout the food production life cycle, nutritional properties, and reuse optimisation. Research has shown that the food system's environmental impact is very high and will increase with the growing population. Although some initiatives have been implemented to decrease the environmental impact, they are currently limited in scale and have a minimal global impact. Many authors show that the most significant environmental impact comes from the farming stage of the process, as we have seen previously. To implement the three suggested "Design for X" approaches—DfSS, DfORU, and DfEO—in food product ecodesign, it is important to consider the differential environmental impact at each stage of the food production process. Figure 1 shows that different stages and parts of the food production system have different environmental impact values. The highest impacts usually come from the farming stage or the production of agricultural raw materials [40].

The application of ecodesign tools in the food industry is limited, and most approaches so far have dealt with eco-efficiency improvements at individual stages of the product life cycle [30,41]. Most studies are devoted to food packaging [42–44], packaging in general [25], or food waste biotransformation [45]. Other approaches rely on using by-products or waste as raw materials for new product development [30,46] or even by other sectors dealing with feed, extraction of oils, and production of biomass and biofuels [46,47]. Despite proposed solutions for nutrient recycling, the circular food system is at the early stage of conceptualisation and does not yet comply with the requirements of a circular economy. However, when thinking about promoting dietary trends from an ecodesign perspective, it would be essential to start upstream and include in the selection of more sustainable raw materials, such as plant-based food sources. From this perspective, ecodesign strategies may offer viable solutions to the sustainable use of food biomass.

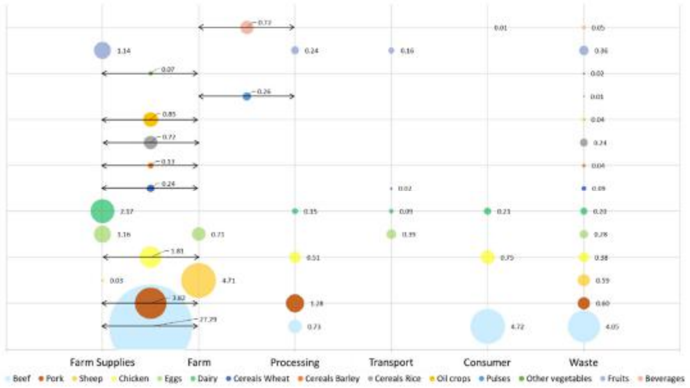

Figure 1. Greenhouse gas emissions (GHGEs) of different food product categories (see bottom coloured legend). The numbers represent the average impact values from some studies on kg CO_2 eq released per 1 kg of the product; the vertical lines represent the stage of the food chain to which the impact relates. When the impact relates to two stages, it is placed in the middle with a horizontal arrow connecting the stages. The absence of a circle in a given stage shows that no data were available in the literature. The consumer stage includes impacts from retail, restaurants, and other parts of the food service sector; waste represents the environmental impact of the food chain accumulated in waste at the end of the chain. Adapted from [48–80].

2.2.1. Design for Sustainable Sourcing (DfSS)

By looking at Figure 1, it is possible to see that the highest environmental impacts of the chain are connected to sourcing the raw materials, in this case, agriculture. One of the viable strategies recognised in several studies to reduce the overall environmental impact of the food system is to switch to a more plant-based diet [6,81]. This diet change is based on the principle that different diets have different environmental impacts [1,2,6,82,83]. It is known that, for example, meat and animal-based products have a higher environmental impact [5,84] when compared to plant-based products [6,85,86] (Figure 1). Several governmental guidelines support a change towards more plant-based diets, but difficulties in implementation, namely due to consumer resistance [87], ask for tools that help this transition. The application of a concept such as ecodesign could be a way to promote this transition.

As the highest impacts come from the production stage, this should be the first point to be targeted with ecodesign. The current unsustainable intensification of agricultural production to obtain a higher yield per given area of land and time worsens the negative impacts of higher utilisation of inputs, such as fuel, irrigation, fertiliser, and pesticides. DfSS can be achieved via sustainable farming, for example [88]. Currently, a few crops (maise, rice, and wheat) are responsible for almost 50% of humans' daily calorie intake [89], and the repetitive growth of the same crops reduces soil biodiversity and depletes soil nutrients without restoring the nutrient banks [90]. It leads to a higher need for artificial fertilisers, leading to additional environmental damage through biodiversity loss and increased acidification, eutrophication, and ecotoxicity [90,91].

While decreasing the environmental impact of the first step of the food production chain is essential and will impact the rest of the chain, it is not the main point to consider. Social and economic aspects are equally important and probably what the producers will consider when applying any of the suggestions that fall into the DfSS category. First, damaging the soil will make it unsuitable for cultivation much faster than it can renew itself, and the available land for these activities is being reduced [92]. This way, producers will lose productive land, decreasing their profits and increasing the price of fertile plots. With this in mind, reforming these over-used plots is crucial to avoid the loss of arable land. Diversifying the crops that grow in these fields instead of pushing for monocultures could help replenish nutrient banks. In addition to that, this is a DfSS strategy, as it lowers the environmental impact of the current crop production (fewer fertilisers needed).

In addition to diversifying the crops, incorporating underutilised crops could take these benefits further. These crops (both in the field and in consumers' dishes) dropped through the years for different reasons (e.g., agronomic, genetic, economic, cultural aspects, or consumers' preferences) [93,94], leading to the lock-in of agricultural and food systems [95]. Efficient cultivation of underutilised crops, as a DfSS, requires substituting existing crops and implementing, e.g., rotations. Genetically improving some underutilised crops through breeding could be a long-term DfSS strategy that would increase their competitiveness. In addition to looking for alternative crops, changing the current agricultural systems towards new cultivation systems, such as vertical farming, hydroponics, or others, is beneficial. While the current systems focus on higher yields [92,96], agroecological systems have many advantages. From shorter cultivation cycles during the entire year—which translates to higher yields –to no soil pollution or associated limitations, as well as low labour requirements in maintenance and harvesting [97].

As stated previously, any changes in this point of the chain will impact everything down the line. Introducing new crops and cultures can affect populations' consumer habits and nutrition. Firstly, when talking about food production and human nutrition, it is crucial to have enough to feed the growing population and provide them with safe, diverse, and nurturing foods that help maintain the population's health and preserve environmental sustainability [98]. Much debate has been revolving around more sustainable protein sources in this respect. Plant-based protein commonly relies on biomass from oilseeds, cereals, legumes, pulses, and aquatic plants [99]. However, several studies show that there is also growing interest in insect biomass for the development of novel products [100].

Other sources include single-cell and in vitro proteins [101,102]. The production of these alternate proteins has a lower environmental impact than animal proteins [103,104]. Still, Gerber et al. [105] suggested that some technologies and practices help reduce animal protein-based emissions, but while these are not widely used, they are available [106]. For example, diet manipulation and feeding additives have been identified as possible routes to decrease methane production during cattle production, and this could also be seen as a DfSS strategy. Other feeding practices, such as the use of alternative feeds (e.g., straw, corn stover, or others [107]), different options for manure handling, or animal husbandry [105], can also help lower the overall impact of meat production.

The application of this concept can catapult dietary change close to consumers. An increasing number of them define themselves as vegetarian or vegan [108,109]. At the same time, it is known that current consumers are looking for more products labelled as “bio” or “organic” [110]. This way, by implementing and developing sustainable agriculture and animal raising, there will be an increase in such products in the market, making it easier for consumers to change their behaviour. In addition to this, there has been discussion on developing a new label (similar to NutriScore) so that consumers can see the environmental impact of the different products and make a more informed purchase [111,112].

In the long term, changes at this point of the chain will impact consumption habits, affecting the population’s health and well-being. With all this in mind, the environmental impact of the production stage must decrease drastically. Though it is something most producers are aware of, this change should not start only from them but with the support of the government—either financially or through changes in legislation to accommodate and incentivise these changes. For this, governmental figures must be aware of the impact of the current chain and the benefits of improving it. This way, incorporating a person with a background in LCA thinking would help immensely in creating targeted policies that support changes in the production stage.

2.2.2. Design for Optimised Resource Use (DfORU)

Sustainable sourcing of raw materials does not solve all the challenges in the value chains. It is important to assess and optimise the entire life cycle of a product. Life-cycle-based approaches targeted to managing supply chains are proven methods to identify environmental and economic hotspots [113]. LCA set based on DfORU strategies allows for holistic gradings of multiple scenarios to select the optimal conditions for impact minimisation.

The processing stage of food production is typically not characterised by high shares of environmental impacts in the product life cycle, as it has been optimised and regulated over the years [30]. Nevertheless, there is room for improvement, since many industries still do not implement energy-efficient or alternative energy-oriented technologies, even if these are economically and environmentally beneficial [114]. A shift towards the use of renewable sources of energy is a specific example of a DfORU strategy. The efficiency of the strategy is connected to the high impact of non-renewable energy use through GHG emissions. It is also possible to reduce the environmental impact by improving industrial process efficiency by consuming less energy per production unit [114,115]. Technological developments in multiple and different industries can help the food processing industry to improve its environmental footprint. Silva and Sanjuán [116] conducted a literature review of LCA studies on food technologies and identified new technologies that, in addition improving quality attributes and shelf life, contribute to resource savings, such as decreased energy and water consumption and lower GHG emissions.

Currently, the EU is committed to becoming the first climate-neutral continent by 2050, starting by reducing its emissions by at least 55% by 2030 (compared to 1990 levels) [117]. For this, more investment and development are necessary for what is known as green technology—technology that positively impacts both the environment and society [118]. However, the costs of green technology and educating workers on how to use them are still very high [119]. This, allied with the strong inertia that comes from the “technological lock-in” [120], makes it difficult to change from the currently used systems and technologies to clean ones without strong policy influence [119].

In addition to new technologies, another important DfORU is to plan for the current losses in the system, starting with reducing the energy loss of the equipment. Some studies show that machines use only about one-quarter of the energy consumed to work on a given process, whilst the rest can be lost [121]. Another option is recovering these losses and reapplying them in the same or another system. This can be achieved, for example, through the application and utilisation of heat exchangers that can have a high heat recovery rate (up to 80%). This energy can be redirected to heat other products or processes [122]. It is also possible to reduce the overall share of non-renewable energy available in the energy grid of each country. Currently, the highest share of renewable energy in Europe can be found in Iceland at 78.2%, followed by Norway at 74.6%, and the lowest in Luxemburg at 7.0% [123] (data for 2019).

The application of DfORU could lead to the optimisation of industrial processes and a decreased environmental impact, as it deals with the processing and distribution stages of the life cycle of food products. Potentially, applying DfORU ecodesign principles to optimise food system processes could occur via: I) avoiding the utilisation of unnecessary material; II) reducing the overall amount of resources used; III) increasing the proportion of renewable energy consumed during the process; IV) improving the processing and distribution chains. One final way to apply DfORU is to reallocate the by-products towards the beginning of the process or to another industry where by-products can have a new value instead of becoming waste material. Developing novel products from by-products (e.g., olive oil production [46]) could be a viable beneficial strategy for nutrient recycling in food systems. Extracting high-value components for other industries is another example of a viable upcycling strategy [124]. Upcycled components can be used in cosmetic, pharmaceutical, and other industries.

2.2.3. Design for End-of-Life Optimisation (DfEO)

The DfEO ecodesign concept, which deals with reuse/recycling, could be applied in the food system sector. However, this type of design has been used mainly by the packaging sector [125] and is highly likely to reduce environmental impact, mainly in the waste category. In the food industry, very little is recovered—mostly the packaging that is recycled by the end user. This is because the environmental impact accumulated in the food products not utilised at the end of the chain is often overlooked in environmental impact assessment studies [126]. Such a gap is connected to limitations in the system boundaries, information on the composition of food waste, and conceptual approaches considering waste as a “zero burden” material [127].

Waste production from the food system has the second-highest impact on the environment and, for this reason, should be tackled by DfEO ecodesign principles. The current causes of food loss and waste are explained by [128,129] and cross all points of food production—from production to consumer. These include: (i) failure on the chain (e.g., agricultural processes, harvesting, storage, processing, packaging, and commercialisation and subsequent deterioration); (ii) atypical decline in quality caused by damage to the packaging or the product itself; (iii) quality defects (e.g., shape, size, or colour outside imposed standards); (iv) discarding products that are close to, on, or past the “best-before” date; (v) leftover food disposal in households and HORECA sectors; and (iv) recall of products by producer and/or retailer for different reasons (e.g., food allergens, presence of foodborne pathogens, or presence of foreign material). Sales et al. [129] explored research gaps in the system, primarily that by stopping the creation of surplus food, there will be less waste generation at all levels. This brings financial benefits throughout the entire chain that the actors are unaware of.

Though the percentage of food waste is very high, currently, there are no available data on its average composition or even how much of it is avoidable or unavoidable waste, especially at the consumer level. Further, the source of waste is often described via approximations [12]. Because of this lack of knowledge, it is challenging to decrease waste throughout the entire life process. As stated, processing usually leads to lower waste production [17], possibly due to longer expiration date. Therefore, increasing the shelf life of food products could potentially reduce the environmental impact of food products, but no studies support this. According to the European Waste reduction hierarchy, preventing and reusing food production is preferable to pursuing waste management, both environmentally and economically [36,130]. Currently, the prevention of waste generation is tackled through donations to food banks, soup kitchens, and shelters or channelling the surplus to the animal feed industry. Other possibilities include converting biomass into biofuel [131,132] or into novel food or feed (microalgae or insects) [133,134].

An emerging DfEO ecodesign innovation concerns food biomass at the end of the chain. It consists, for example, of the reuse of food biomass close to the expiry date for human consumption and reprocessing to extend its shelf life. During a product's shelf life, different reactions can occur (chemical, physical, and/or biological), caused by different factors (microorganisms, enzymes, physical, and/or chemical degradation) that decrease its safety and quality and render it unacceptable [95]. When considering reprocessing a food product, the timeframe for when the product should be removed from retail and channelled for reprocessing is critical. It is known that the "best before" date indicates the period of quality retainment in a wide range of products. The "use by" label indicates the date until the food can no longer be eaten safely and is usually found on perishable products [94]. These two concepts provide an estimate of when the products could, potentially, be recalled and reprocessed. For products with "use by", collecting and reprocessing before the given date is imperative since food safety cannot be guaranteed after this point. This strategy, if well implemented, could help with food waste prevention, the first point in the waste hierarchy.

"Reuse" is defined as "any operation by which the products or components that are not waste are used again for the same purpose for which they were conceived" [36]. Such a definition, when applied to food products, indirectly implies applying the same or similar processing procedures to the ones used initially to ensure quality and safety for human consumption. It requires specific developments in packaging design (separation, recyclability, safety, and reuse) and biomass reprocessing. Soro et al. [135] enumerated several points that measure the mechanisms of deterioration that occur during a product's shelf life. These are used to evaluate a product for commercialisation and consumption, ranging from physical or chemical analysis to sensorial evaluation.

In order to reprocess food biomass that is close to the "best before" or "use by" date, classic and emerging technologies can be used. Classic technologies include, e.g., thermal processing (mild and severe) [136,137]. The use of novel technologies, e.g., High-Pressure Processing (HPP), has the advantage of obliviating the unpacking and repacking stages of the process, allowing for product processing inside the original package. This brings benefits from an economic and environmental standpoint, as long as the package is resistant to high pressures [138]. Additionally, HPP requires homogeneous products to ensure evenly distributed pressure [139]. Another limitation is that specific food matrices (e.g., powdered matrices) cannot be processed with such a technology.

One consideration of this innovative ecodesign strategy is that reusing food biomass at the end of the chain must ensure safety for human consumption and sound quality [140]. Another critical factor is the potential increase in the environmental impact, which should be lower than the footprint of a new product. This raises the question of the viable number of potential reprocessing cycles (Figure 2), as avoiding the environmental impact of the food biomass created by a "recycled" food product can snowball into a much more significant environmental impact. In addition to that, further processing and reprocessing of the same product can lead to the release and/or creation of new components in the matrix. These can be neglectable if they cause no harm to human health but should be dealt with if they are potentially hazardous [141]. Finally, the reprocessed product should be economically reliable, as both producers and consumers aim for affordability—the (possibly) "new" and "recycled" product should not be more expensive than it was initially unless it becomes a product of increased value.

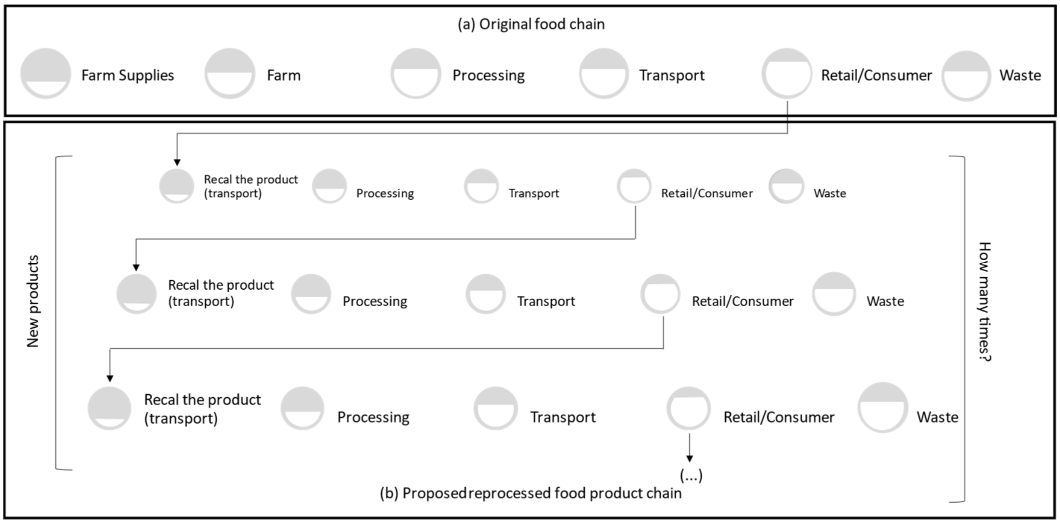

Figure 2. Relative environmental impact of (**a**) a generic food product (original food chain) and (**b**) potentially increased accumulated impact of a reprocessed food (reprocessed food product chain). The shaded circles represent the product's total environmental impact, whereas the white parts represent each stage of the chain's contribution to the total impact. While avoiding waste production via diversion and repurposing of food biomass, there will be a limit to the number of cycles that make recycling viable without increasing the product's environmental impact when wasted initially. Source: authors.

A final concern is the labelling of these new products. Since the reprocessed product no longer represents the original product, the label should reflect this change. This is especially important when considering nutrient loss or alterations in the nutritional composition of the food product. Currently, there is no regulation for this type of product since the research in food biomass reprocessing for further reuse as food is very limited and, to the best of our knowledge, has never been implemented in commercial practice. Nonetheless, current regulations indicate that food labels should include different relevant information. This includes: the name of the food, ingredient list (including ingredients that can cause allergies or intolerances), quantities of ingredients, net quantity of the food, "best before" or "use by" date, any special requirements for storage or use conditions, name or business name and address, country of origin, nutrition declaration, and, in the case of having more than 1.2% of alcohol in volume, the actual alcoholic strength [142]. The regulations also point to the need to identify the type of processing applied (homogenised, irradiated, cold-pressed) [143].

3. Ecodesign Principles to Support the Sustainable Development Goals (SDGs)

As the article shows, cattle production is responsible for the largest share of the impacts, and between 22 and 29% of GHGs released could be reduced by changing to plant-based diets [144,145]. It has been suggested that the environmental impact of current diets could be reduced by 20–40% by decreasing meat, dairy, and egg consumption by 25–50% [146]. Reducing agricultural GHGs through the DfSS strategy could increase the safe space for interconnected food and climate systems [88]. Research shows that the low efficiency of biotransformation of raw materials leads to only 15% of the consumed energy and protein being delivered to humans, whilst the remaining 85% are lost. [147]. By applying mitigation strategies in animal protein production, we could reduce around 30% of current emissions [105]. Additionally, preliminary indications highlighted the potential of ecodesign principles to reduce inefficacy per hectare of food production (93%) and increased water use efficiency, soil health, fertility, and pest control by shifting from current cultivation systems to alternative ones [148]; the amount of avoidable food waste at the consumer point could potentially result in reductions in GHGs of 800–1400 kg/tonne of food waste [149]; resource consumption with the use of new technologies and processes [150]: (i) to 30% in water use; (ii) between 6 and 25% in fuel use; and (iii) between 11 and above 90% in herbicide, pesticide, or herbicide use, and others [151].

With this in mind, the potential improvements in the food supply chain could be summarised into a single ecodesign framework for food products (Figure 3). The framework is based on life cycle thinking and targets different parts of the supply chain for maximal positive and synergetic effects. The framework supports the development of new technologies and methods for reducing the environmental impact along the supply chains. This is especially relevant for new products and novel protein sources. Therefore, the framework first considers reductions in impact at the most impacting part of the production chain through the development of techniques for sustainable sourcing (e.g., alternative protein sources, new types of biomass, and cell cultivation technologies) [152], estimating that reductions in impact might reach 20–30%. The proposed framework also targets the next most significant impacting part of the chain—reducing food waste through reusing or repurposing the food products at the end-of-life point, targeting a reduction in impact of around 15–20% [152]. Moreover, the last strategy should be aimed toward designing a production chain with minimal use of raw materials and an improvement of around 5% [152].

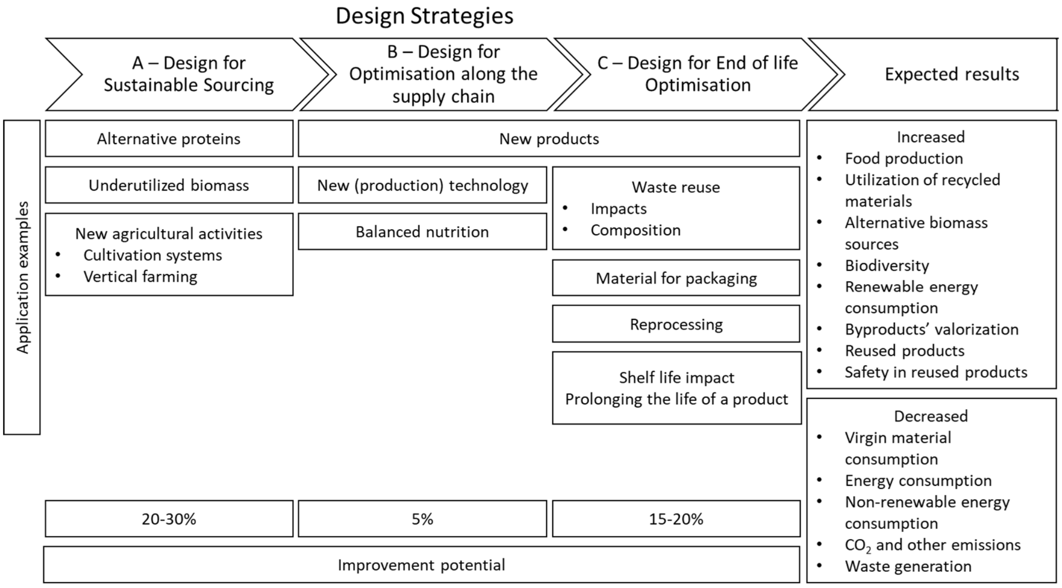

Figure 3. Conceptual ecodesign framework for sustainable food production and compilation of literature suggestions. Implementing the suggested examples can lead to a variable improvement in the system's environmental impact, from 5% to 30%, depending on the target point. Source: authors.

While applying ecodesign principles to different components and stages of food production is viable for reducing food's environmental impact, integrating ecodesign concepts to the extended production chain level, including nutritional properties, could leverage much higher environmental benefits [153]. It requires an integrative approach, including different life cycle stages, analysing biomass properties and addressing socio-economic needs via the Sustainable Development Goals (SDGs) [154]. The United Nations has recognised that many food production and consumption points still fall short of the SDGs [155]. Most SDGs can be linked directly or indirectly with the food system and each other. The application of ecodesign is foreseen as one of the potential strategies to deal with multiple SDGs: 6 (energy), 8 (economic growth), 11 (sustainable cities), 12 (sustainable consumption and production), 13 (climate change), 14 (oceans), and 15 (life on land) [156].

Figure 4 shows a generic view of the life cycle of a food product. As mentioned above, applying ecodesign strategies will impact a product's production and life cycle chain. With this, some outcomes can be easily predicted, such as decreased energy consumption, gaseous emissions, increased biodiversity, and renewable energy consumption. These predictions are based on the literature and the benefits of applying the concept in other areas. This way, the application of this approach supports different SDGs.

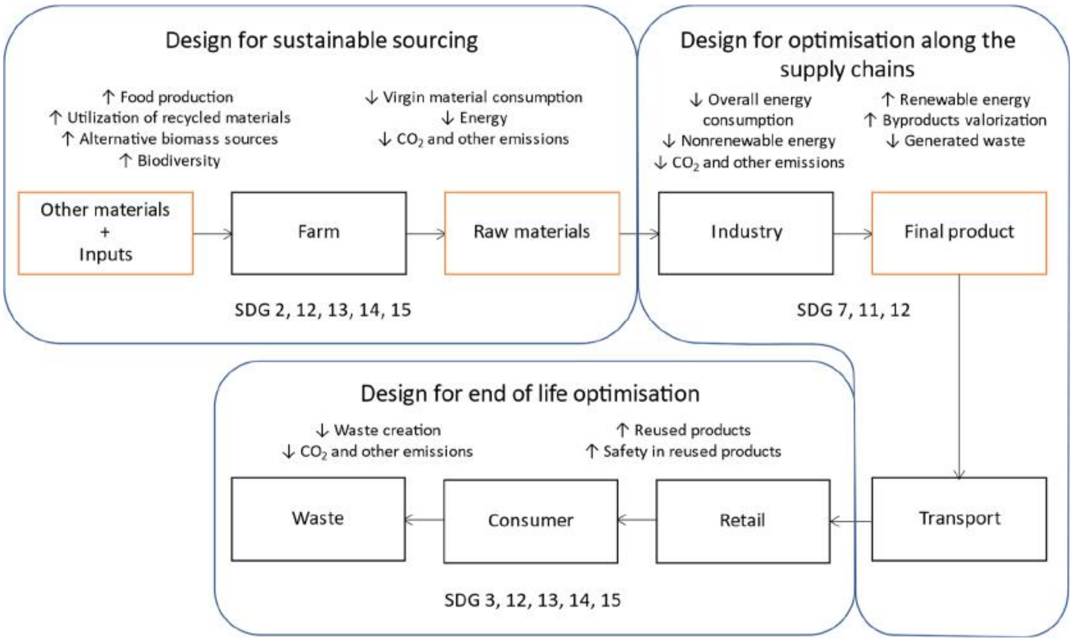

Figure 4. Potential implementation of the three main components of the ecodesign principles in a generic food chain—(1) design for Sustainable Sourcing, (2) design for optimised resource use and (3) design for end-of-life optimisation. This implementation is in line with relevant Sustainable Developing Goals (SDGs). Possible outcomes of implementing such concepts can be found inside the same rectangle. Downwards arrow—Decrease; Upwards arrow—Increase. SDGs: 2—Zero Hunger; 3—Good Health and Well-being; 7—Affordable and Clean Energy; 11—Sustainable Cities and Communities; 12—Responsible Consumption and Production; 13—Climate Action; 14—Life Below Water; 15—Life on Land. Source: authors.

4. Conclusions

Ecodesign strategies have the potential to deal with the main environmental hotspots of agrifood chains efficiently. This review analyses the available literature on the ecodesign principles, proposing a conceptual framework of ecodesign strategies applied to food products. It applies LCA principles with strategies targeting the most significant improvements for implementation. This review shows how three main ecodesign strategies (DfSS, DfORU, and DfEO) can improve efficiency and reduce food products' environmental impact at different supply chain levels. In addition to the critical benefits that result from reduced waste generation, most benefits arise when ecodesign principles target the production stage (raw material selection and improved agricultural practices). Benefits will also derive from fine-tuning the food processing industry and returning nutrients to the food system via food product reprocessing and reutilization. Ecodesign approaches to food product generation can also support dietary changes towards more plant-based options.

New labelling schemes that quantify the genuine environmental positivity of food products can arise from applying ecodesign principles that favour more sustainable raw materials. However, further research is needed to define the potential for future application of ecodesign principles for food products along the agrifood supply chains. Such improvements and potential synergetic and indirect effects (nutritional and safety changes affecting human health) should be further studied. To implement these concepts, there must be people at all points of the chain who are aware of them and trying to implement them to improve the environmental impact and the product as much as possible. It could start with ecodesign principles taught in university curricula and educators that help guide thought and processes when designing a new product or food solution. Despite the limitations, the proposed framework, for the first time, provides a theoretical basis for ecodesign studies in food products. In addition to this, it will be beneficial to analyse the chain where someone will apply the ecodesign concept and develop an algorithm to find which point in food chain production should first be targeted to improve the environmental impact.

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