CHAPTER 1. FOOD AND AGRICULTURE SYSTEM

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Executive Summary

No area of human activity is more essential to society than a sustainable Food and Agriculture System (FAS). With projections that the global population will grow to as much as 10 billion by 2050, there is increasing concern as to how this system should be transformed to feed the population while contributing to sustainable development. Agricultural productivity has been a consistent and important focus of attention during the 20th and 21st centuries, with good reason, as it aimed to feed such growing world population. While a driving goal for the FAS remains providing safe and affordable food numerous emerging factors challenge our present and future food and agriculture system.

This chapter addresses the decarbonisation of the Food and Agriculture System by considering the advancement of many scientific and technological developments that may transform the existing one. The global FAS is responsible for about 33% of total anthropogenic emissions according to IPCC (2022)[1] but this percentage can vary somewhat according to other reports and how the FAS is defined. The chapter focuses on: the characterisation of the FAS, from domestication to today's highly complex and adaptive system; both the impact of the FAS on the environment and the effect of the environment on the FAS (climate change); the role of the FAS as an energy supplier as well as an energy consumer; the effects of changing food preferences and dietary changes on emissions and energy; the role of the FAS in meeting Sustainable Development Goals (SDGs); the challenges of socio-technical innovations across global and local levels; and the impact of such specific technologies as renewable energy sources (solar power, wind, geothermal and bioenergy, including biofuels and biochar), digital agriculture, nanotechnology, biotechnology (CRISPR), regenerative agriculture/agroecology, agroforestry, electrification, the circular economy, and synthetic biological food developments.

Technology played a pivotal role in the impressive agricultural transformation that took place in the 20th century. And technologies should similarly play an essential role in addressing current and future sustainability challenges that bring together agriculture, food, health, energy, climate, environment, and social justice. While technology should be considered a necessary and useful resource, there is no magic bullet, nor a 'one size fits all' solution. Any technology may offer potential avenues for progress and provide benefits but also bring about drawbacks and contribute to the emergence of new problems. In addition, the profound changes that are required today will depend on a series of many complementary solutions, as no single one might address the breadth and depth of this challenge. These basic assumptions first call for the need to generate appropriate metrics and assessments that account for the capacity of technology to contribute, not only to decarbonisation but also to all the dimensions of sustainability as there might be trade-offs among them. This is challenging: most assessments are context- as well as time-, space-, and scale-specific, accounting for complex and uncertain processes, and require methods and indicators that are not always available. These assumptions also call for context-specific design processes. This is essential to jointly consider technological resources, the innovation process, and the contributions to addressing sustainability concerns.

Agricultural and food systems are quite context-specific. Their transformation relies on locally adapted practice changes that depend on resources and available technology, know-how, risk management, etc., and may involve various stakeholders with divergent vested interests. In addition to the discussions on its impacts, technology implementation may thus face resistance related to values and interests, conflicts of interest, risk management and path dependency that make it very complex to analyse its political economy. Finally, technology may have a controversial dimension and, alongside growing suspicion concerning technology and the spread of fake news, may become a polemical and polarising issue. To address such challenges, the chapter provides a critical review of both the benefits and drawbacks of technology. It identifies four different scenarios taking into consideration the main drivers, and finally presents key messages and recommendations.

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[1] IPCC-AR6-WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

1. Introduction

The purpose of this chapter is to address decarbonisation in the Food and Agriculture System (FAS) by considering the advancement of numerous scientific and technological developments that can transform the existing FAS. It focuses on: the characterisation of the FAS from domestication to today's highly complex and adaptive system; both the impact of the FAS on the environment and the effect of the environment on the FAS (climate change); the role of the FAS as an energy supplier as well as an energy consumer; the effects of changing food preferences and dietary changes on emissions and energy; the role of the FAS in meeting Sustainable Development Goals (SDGs); the challenges of socio-technical innovations across global and local levels; and the impact of such specific technologies as renewable energy sources (solar power, wind, geothermal and bioenergy, including biofuels and biochar), digital architecture, nanotechnology, biotechnology (CRISPR - clustered regularly interspersed short palindromic repeats) , regenerative agriculture, electrification, the circular economy, and synthetic biological food developments.

There is no area of human activity more essential to society than a sustainable Food and Agriculture System. With projections that global population will grow to as much as 10 billion by 2050, there is an increasing concern as to how this system should be transformed to feed this population while contributing to sustainable development. Agricultural productivity has been a consistent and important focus of attention during the 20th and 21st centuries, with good reason, as it aimed to feed a growing world population. While providing safe and affordable food remains a driving force for the FAS, emerging and numerous factors nevertheless challenge our present and future FAS. These include: the impacts of the FAS on the environment (gaseous emissions, climate change and pollution, the degradation of water and biodiversity); distrust in science and technology; increasing urbanisation and changing food preferences; globalisation, droughts, international trade, integrated value chains and price volatility; regulation; energy; the economic viability of rural communities and political stability; the impact of climate change on food production; and, more recently, a recognition of the disruptions that major events, such as a pandemic or a war, can create for the FAS. The following questions are also critical to address: (i) Will the food system reduce or increase hunger and poverty among the poor?, (ii) Will the system enhance or decrease equity and access to food for a healthy and productive global population?

Our existing FAS has evolved since the domestication of plants and animals, traced as far back as approximately 11,000-9,000 BC[2]. From its origin, the FAS has fundamentally been a land-based system with the soil being its one consistent factor. However, emerging subsystems of precision controlled-environment indoor agriculture, as well as alternative protein food systems -- largely established in soilless-based indoor facilities -- are experiencing significant growth.

We thus propose that the evolution of the FAS consists of four relevant periods, which are described below.

i) **Before domestication.**

ii) **From domestication to 1960:** a time of agricultural expansion during which production is correlated with land under cultivation.

iii) **Agricultural industrialisation:** when increase in yield then made it possible to disconnect production and land under cultivation.

iv) **The expansion of landless agriculture:** its increasing role relies on the emergence of synthetic foods (white and green chemistry) and indoor controlled environment agriculture.

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[2] Zeder, M. The origins of agriculture in the near east. 2011. Current Anthropology. https://www. jstor.org/stable/10.1086/659307

Box 1. A farmer recounts how agriculture was transformed in the last 100 years in the UK

We, in agriculture and food, need to reduce the energy we use and the Greenhouse Gas (GHG) pollution we create daily adding to global warming. In the 1930s ruminating animals were creating methane gas. Steam engines using coal producing CO_2 provided energy to drive corn thrashing machines and some plowing. The remainder of work in the fields was undertaken by horses, pulling all the implements. With men most often walking behind, to plow, cultivate, plant the seeds and harvesting all the crops, with root crops lifted entirely by hand. No artificial energy used. We had no artificial fertilisers, rather using burnt limestone and farmyard manure from food producing animals. No sprays of seed treatments were used. Herdsmen rose by candle, hand milked by lantern light, cooled the milk with stored rainwater, over a surface cooler, filtered into churns. Then delivered by pony and trap to local customers, with a measure from a bucket direct to a customer's jug, the pony moving from house to house. Meat was slaughtered locally, butchered and delivered in the same way. Corn was thrashed and delivered by horse drawn wagons to local steam driven mills producing the flour for baking by local village bakers.

Two World Wars and the subsequent rapid development of the internal combustion engine, plus the need for self-sufficiency in food supply, changed agricultural life completely. Milking machines replaced men; tractors replaced horses. Energy in the form of oil and electricity provided the base to feed a rapidly increasing world population and distribute food around the world – thus unfortunately and sadly contributing to an earth-threatening rise in atmosphere temperature we must counter.

Since the 1960s and, just like other sectors of the economy, food supply underwent an agricultural revolution decoupling land use and production and relying on a carbonisation of food and agriculture systems that is well documented by many scholars. What is known as the modernisation of agriculture (or the 'green revolution' in developing countries), encouraged by active agricultural and price stimulating policies, acknowledged such pillars as:

- the use of fossil energy to support mechanisation and motorisation, resulting in an incredible increase of both labour and land productivity, as well as the extension of cultivated land in particular through its encroachment into the forest as can still today be observed in Amazonia and South-East Asia;
- the mobilisation of chemical inputs in all agricultural practices (fertilisers, herbicides, pesticides, etc.);
- important public and private investment in genetics, genetic improvement, and seed delivery systems;
- the development of long-distance value chains, requiring transport and processing infrastructures and, as a consequence, energy consumption;
- and the significant expansion of irrigated areas based on previous technological assets and public investments in large-scale infrastructure.

Despite population growth, food availability per capita has been continuously growing at the global level because of the modernisation of the agricultural sector and a subsequent increase in production (*Fig. 1.1.*) that has come to exceed the rate of population growth (Paillard et al., 2014)[3]. Yet, while this transformation generated new nutrition concerns, for instance those related to obesity, this has not been sufficient to eradicate hunger, as the number of persons suffering from undernutrition remained stable over the last decades[4].

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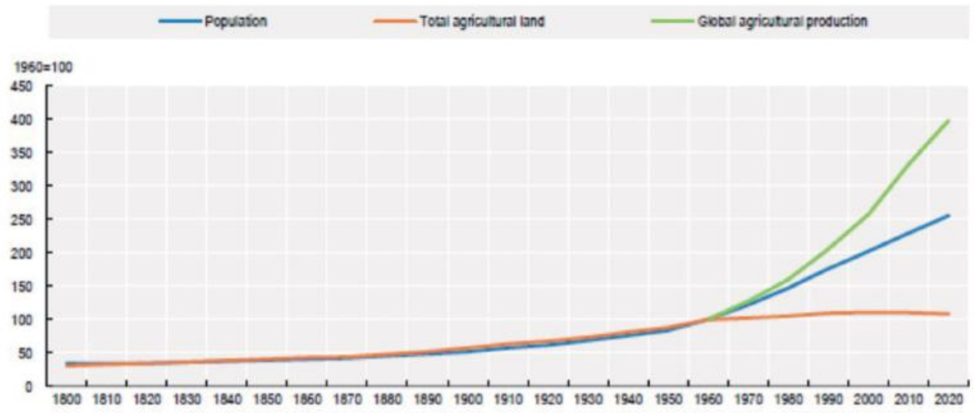
[3] Paillard, S., Treyer, S., & Dorin, B. (2014). Agrimonde–scenarios and challenges for feeding the world in 2050: Springer Science & Business Media.

[4] HLPE. 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from https://www.fao.org/3/i7846e/i7846e.pdf.



Source: Population data from Maddison's historical statistics for 1820-1940; UN Population Division for 1950-2010; 1800 and 1810 extrapolated from Maddison. Agricultural (crops and pasture) land data for 1800-2010 from the History Database of the Global Environment (HYDE 3.2), Klein Goldewijk et al. (2017). Global agricultural production data for 1960-2010 from FAOSTAT (Net Agricultural Production Index); data for 2020 from OECD/FAO (2020), "OECD-FAO Agricultural Outlook", OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-data-en.

Fig. 1.1. Population, food production, and agricultural land use from 1800 to 2020
OECD 2021, "Making Better Policies for Food Systems", OECD Publishing. Paris, Fig 1.7 at page 28. Order License ID 1291258-1
https://www.oecd-ilibrary.org/agriculture-and-food/making-better-policies-for-food-systems_ddfba4de-en
URL direct access: https://www.oecd-ilibrary.org/sites/edf73cce-en/index.html?itemId=/content/component/edf73cce-en

2. Complex interactions between agriculture, food, water, environment and energy

The FAS can be characterised as a complex adaptive system that operates across a broad spectrum of economic, biophysical and socio-political contexts[5]. It is at the intersection of some major global issues: food, energy, water, population, land use, and development. Biofuel production and the policies used to support its development can, for instance, be related both positively and negatively with each of the four dimensions of food security – availability, access, utilisation (nutrition) and stability[6]. The impact and feedback links between biofuels and food security require assessments at both global and local levels, recognising ecosystem services and taking into account context specificity.

As already stated, the evolution in the food system has created dramatic consequences and drawbacks on the environment[7, 8]. The emergence of these environmental concerns and global actions to prevent catastrophes (climate change, biodiversity loss and land degradation) call for decarbonising the FAS.

- Past transformations of the FAS led to the deterioration of agroecosystems and great losses of specific and genetic biodiversity. In turn, these losses have hampered the FAS in different ways, resulting in the decrease of diversity in food supply and its nutritional value[9, 10, 11].

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[5] National Research Council. 2015. A framework for assessing effects of the food system. The National Academies Press. Washington D.C.

[6] HLPE. 2013. Biofuels and food security. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2013. https://www.fao.org/3/i2952e/i2952e.pdf

[7] Caron, P., Ferrero y de Loma-Osorio, G., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I., . . . Verburg, G. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. Agronomy for Sustainable Development, 38(4), 41. DOI: 10.1007/s13593-018-0519-1

[8] Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., . . . Murray, C. J. L. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet. DOI: 10.1016/s0140-6736(18)31788-4

[9] HLPE. 2017b. 2nd Note on Critical and Emerging Issues for Food Security and Nutrition. 23. Retrieved from https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/Critical-Emerging-Issues-2016/HLPE_Note-to-CFS_Critical-and-Emerging-Issues-2nd-Edition__27-April-2017_.pdf

[10] Hainzelin, E. 2019. Risks of irreversible biodiversity loss. In S. Dury, P. Bendjebbar, E. Hainzelin, T. Giordano & N. Bricas (Eds.), Food systems at risk. New trends and challenges (pp. 59-62). Montpellier, France: CIRAD, European Commission, FAO.

[11] FAO. 2019. The state of world's biodiversity for food and agriculture J. Bélanger & D. Pilling (eds.)
FAO Commission on Genetic Resources for Food and Agriculture Assessments, (pp. 572). Rome: Food and Agriculture Organization.

- The global food and agriculture system is responsible for up to one third of anthropogenic greenhouse gas (GHG) emissions and is therefore a major driver of climate change[1, 12]. This percentage can vary from 25% to 33% according to different reports. According to IPCC (2022)[1], 24% out of 33% are due to the agricultural and livestock sectors, whereas 9% are generated by Land Use, Land Use Change and Forestry. Emissions from direct on-farm energy use, agricultural practices and fishing are responsible for approximately 1% of global CO_2 emissions, 38% of global methane emissions (CH_4, essentially related to ruminants' production), and 79% of global N_2O emissions (essentially related to rice production). Quantitatively, agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4$/yr and 6.6 ± 4.0 MtN_2O/yr or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_{2e}$/yr respectively between 2010 and 2019[1].
- Food production, and consequently the livelihoods of billions of people, especially the most vulnerable, including small farmers, is impacted and will be even more in the coming decades by the effects of climate change[13].
- Although the demographic transition is mainly behind us (apart from Sub-Saharan Africa), consumption trends, including the possible increase of animal source products in the Global South, point to dramatic developments with figures ranging from 50 to 100% increase in production towards 2050[11].

The FAS system is indeed at the forefront of environmental issues, both as a main contributor to global change, but also as a potential victim or rescuer. It is therefore appropriate to question the capacity of our FAS to feed the global population in a sustainable and resilient manner. Gerten et. al. (2020)[14] conclude that our system, as it currently stands, could at best feed only 4 billion people if all planetary limits were respected. To avoid this predicted failure, four global mitigation 'strategies' are generally proposed: (i) a transition to a healthier diet with less meat; (ii) technological improvements to intensify food production and processing on a sustainable basis; (iii) an important reduction of food loss and waste; and (iv) a political and socioeconomic framework that ensures reduced inequality, lower population growth and strong and coordinated governance of land and oceans.

The challenge is to ensure that new practices and novel technologies, the emergence of increasingly circular and soilless based food systems and the co-existence with more traditional FAS will continue to provide accessible, healthy, tasty, and inexpensive food while reducing its contribution to negative global change and increasing resilience to various risks. The FAS can facilitate mitigation of emissions in a number of different ways. Specifically, it can reduce emissions within the food and agriculture sector, can sequester carbon from the atmosphere, and provide raw materials to enable mitigation within other sectors, including energy, industry, or the built environment.

Food is produced and processed by hundreds of millions of farmers and intermediaries, with a significant global impact on the environment. Do differences in environmental impacts depend on specific food products? It is an intriguing and challenging question to answer but a comprehensive study by Poore and Nemecek (2018)[15] has consolidated data on multiple environmental impacts from about 38 000 farms and approximately 1 600 processors, types of packaging and retailers for 40 different agricultural products across the world in a meta-analysis comparing various types of food production systems. *Fig. 1.2.* illustrates differences in GHG emissions/unit of product. Although emissions can be subject to substantial variability along the food chain, it is nevertheless illustrative of the fact that large differences exist between plant sources compared to animal products. Hence the importance of dietary choices.

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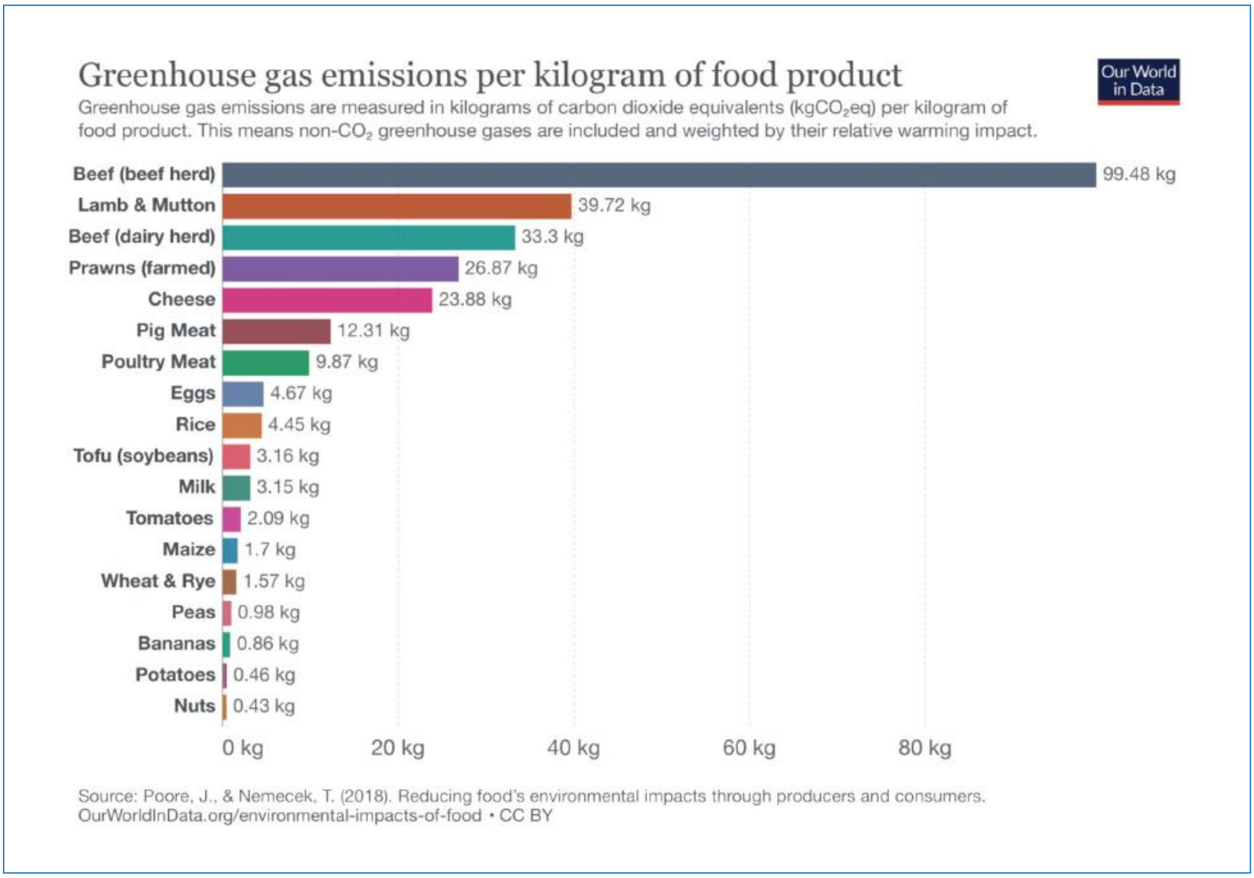
[12] Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F. N., Jain, A. K. 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nature Food, 2(9), 724-732. doi: 10.1038/s43016-021-00358-x

[13] IPCC. 2018. Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.) (pp. 630).

[14] Gerten D., Heck V., Jägermeyr J., Bodirsky B. L., Fetzer I., Jalava M., Kummu M., Lucht W., Rockström J., Schaphoff S., Schellnhuber H. J., 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. Nature Sustainability, Vol. 3, p. 200–208, 2020. https://doi.org/10.1038/s41893-019-0465-1

[15] Poore, J. and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392): 987-992.DOI: 10.1126/science.aaq02


Greenhouse gas emissions per kilogram of food product

Greenhouse gas emissions are measured in kilograms of carbon dioxide equivalents (kgCO_2eq) per kilogram of food product. This means non-CO_2 greenhouse gases are included and weighted by their relative warming impact.

Source: Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers.
OurWorldInData.org/environmental-impacts-of-food • CC BY

Fig. 1.2. Greenhouse gas emissions per kg of various food products (Poore and Nemecek, 2018[15]; Richie and Roser, 2020)[16]

Ritchie and Roser (2020)[16] have worked with data available from the meta-analysis by Poore and Nemecek (2018)[15] to develop a visualisation of the share of the FAS compared to total emissions and by source across the supply chain (*Fig. 1.3.*). As previously noted, depending on source and definition, the food system is reported to create about 25% to 33% of anthropogenic GHG emissions[17]. It should be noted that refrigeration and packaging account for about 10% of global FAS emissions or approximately 1/2 of the emissions of the supply chain factors[18]. Also, it should be noted that emissions vary substantially depending on the product.

From a study in the EU, in addition to GHG emissions, the FAS impacts the environment in other ways such as toxicity phenomena, eutrophication, acidification, air and water pollution, etc., as shown in *Fig. 1.4.* which displays the relative impacts of the six stages (activities) for 15 environmental categories. It shows that the agricultural phase (vertical stripes) has the greatest environmental effect in many impact categories because it includes impacts of all agronomic and production activities. The second largest impact activities are process and distribution (logistics), due to the use of thermal and electrical energy. Other lifecycle phases only make minor contributions to the overall impact[19].

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[16] Ritchie, H. and M. Roser. 2020. Environmental Impacts of Food Production. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/environmental-impacts-of-food

[17] Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, E, Tubiello, E., Leip, A. 2021. Food systems are responsible for a third of global anthropogenetic GHG Emissions. Nature Food, 2, 198–209. https://doi.org/10.1038/s43016-021-00225-9

[18] FAO. 2021. Food systems account for more than one third of global greenhouse emissions. Rome, Italy: United Nations. http://www.fao.org/news/story/en/item/1379373/icode/.

[19] Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., and Sala, S. 2017. Environmental impacts of food consumption in Europe. J. Cleaner Production 149: 753-765. https://doi.org/10.1016/j.jclepro.2016.06.080.

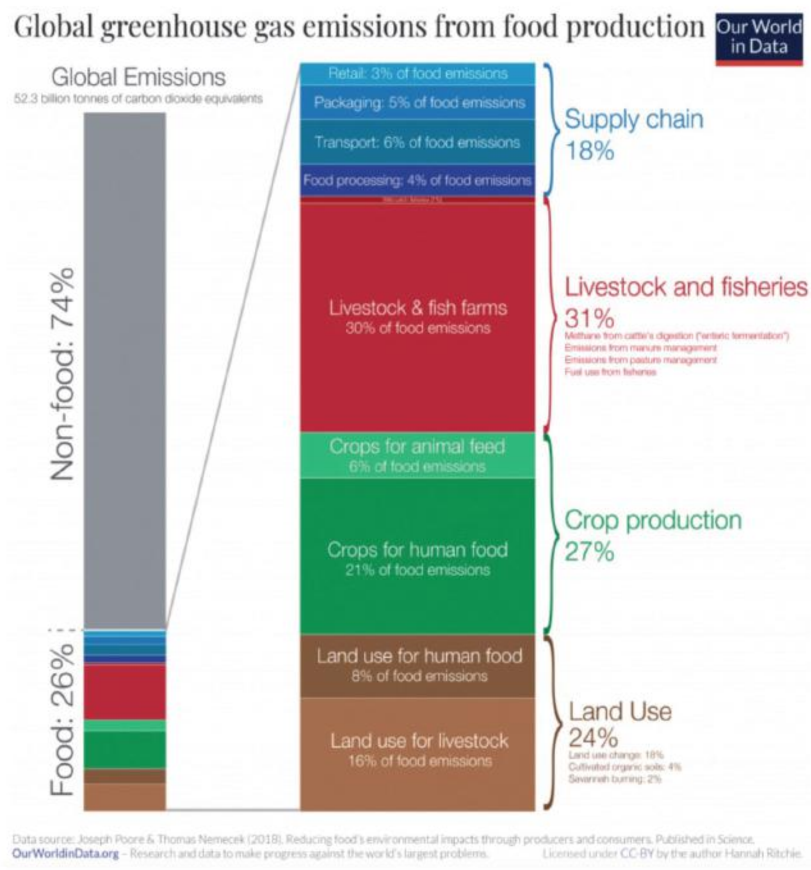

Fig. 1.3. GHG emissions from the food system, total and by areas.
https://ourworldindata.org/environmental-impacts-of-food, Author: Hannah Ritchie

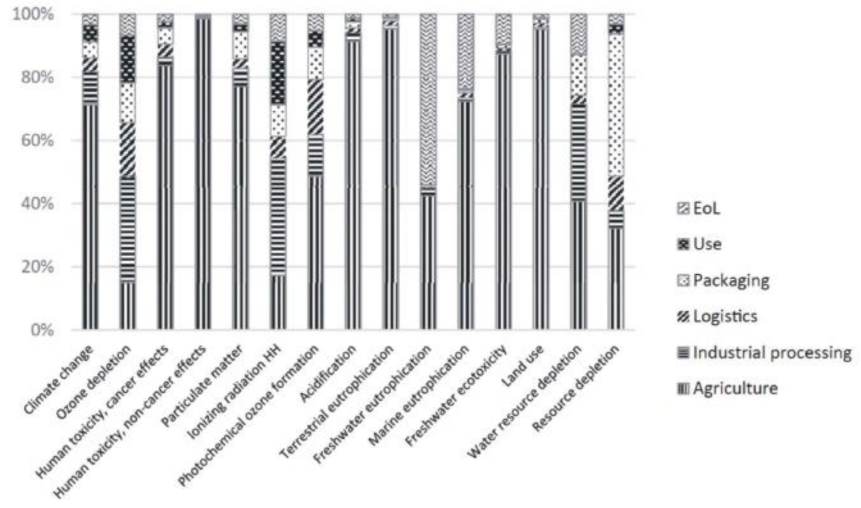

Fig. 1.4. Relative contribution of the 6 life-cycle phases to the impact of the entire basket in each impact category for the EU. (Notarnicola, et.al., 2017)[19]. [EoL = End of Life]

Source: Bruno Notarnicola, Giuseppe Tassielli, Pietro Alexander Renzulli, Valentina Castellani, S. Sala, 1 January 2017, "Environmental impacts of food consumption in Europe", Journal of Cleaner Production, Elsevier, CC-BY-NC-ND 4.0. CCC Order License ID 5471400467922
https://www.sciencedirect.com/science/article/pii/S0959652616307570
Direct URL: https://ars.els-cdn.com/content/image/1-s2.0-S0959652616307570-gr2_lrg.jpg

2.1. The Food and Agricultural System: a definition and challenges for the future?

The FAS can be defined as the way social groups organise to access food[20] and this concept helps characterising the complexity of food related issues. *Fig. 1.5.* provides a conceptual framework for analysing and designing the FAS. The High-Level Panel of Experts of the UN Committee on World Food Security (HLPE/CFS) has proposed that the FAS "gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes"[21, 22]. To escape the assumption that food consumption would rely on rational choices that optimally articulate supply and demand, the framework introduces the notion of food environment, defined as "the physical, economic, political and socio-cultural context in which consumers engage with the FAS to make their decisions about acquiring, preparing and consuming food"[23]. Food environment is thus a social and cultural construct that shapes the FAS and makes it specific from one place to another.

The challenge faced by food production has become increasingly more complex in the 21st century than what it seemed to be in the preceding one. In the 20th century, indeed, any increase in productivity and production would both contribute to addressing the supply needs in order to cope with the demographic transition and at the same time sustain economic growth because of increasing demand. As explained above, it now lies at the heart of a complex nexus bringing together health, the environment, energy, and economic and social drivers. In addition, as the agricultural sector is both a consumer and supplier of energy[24] interactions between the agricultural and energy sectors and climate change are incredibly complex and context specific. FAS is thus pivotal in bringing together energy and sustainability concerns. Understanding such challenges and actions thus requires system and transdisciplinary approaches. Among others, the systems approach – a multi-level treatment with dynamic interaction between framework constituents – to the analysis and optimisation of these cross-disciplinary issues is gaining traction[25]. From the perspective of data analysis, artificial neural network applications have also proved to be useful approaches in these complex food-agriculture systems, as evidenced by recent developments[26, 27]. Artificial intelligence is thus playing an increasingly relevant role in providing advanced and affordable technological solutions to the FAS.

2.2. Sustainable Development Goals and the Food and Agriculture System

Because of their many interactions, food and agriculture systems can be considered as major levers to address all sustainability concerns of the 2030 Agenda for sustainable development (*Fig. 1.5.*), and not just its second Sustainable Development Goal (Zero Hunger). This has also led the UN Global Sustainable Development Report to identify food systems and nutrition patterns as one of the six entry points to achieve the 2030 Agenda[28]. This is why the UN Secretary General called for a Food System Summit (and not just about food) which was held in September 2021. The Summit confirmed how and why food systems bring together the issues of food security, human and ecosystem health, climate change, social justice and political stability.

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[20] Malassis L., 1994. Nourrir les hommes. Paris, Flammarion (coll. "Dominos" 16).

[21] HLPE, 2014. Food losses and waste in the context of sustainable food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2014. https://www.fao.org/3/i3901e/i3901e.pdf..

[22] HLPE. 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from https://www.fao.org/3/i7846e/i7846e.pdf

[23] HLPE. 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from https://www.fao.org/3/i7846e/i7846e.pdf

[24] HLPE. 2013. Biofuels and food security. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2013. https://www.fao.org/3/i2952e/i2952e.pdf

[25] Borman G.D., de Boef, W.S., Dirks, F., Gonzalez, Y.S., Subedi, A., Thijssen, M.H., Jacobs, J., Schrader, T., Boyd, S., ten Hove, H.J., van der Maden, E., Koomen, I., Assibey-Yeboah, S., Moussa, C., Uzamukunda, A., Daburon, A., Ndambi, A., van Vugt, S., Guijt, J., Kessler, J.J., Molenaar, J.W., van Berkum, S. 2022. Putting food systems thinking into practice: Integrating agricultural sectors into a multi-level analytical framework. Global Food Security, 32, 100591. https://www.sciencedirect.com/journal/global-food-security/vol/32/suppl/C.

[26] Kujawa, S., Niedbala, G., 2021. Artificial Neural Network in Agriculture, Agriculture 11, 497 (and other papers in this Special Issue). https://www.mdpi.com/2077-0472/11/6/497 ; Jimenez, D., Perez-Uribe, A., Satizabal, H., Barreto, M., Van Damme, P., Tomassini, M., 2008., A Survey of Artificial Neural Network-Based Modeling in Agroecology, in Soft Computing Applications in Industry. Prasad B (ed), p247. Springer-Verlag, Berlin. https://link.springer.com/chapter/10.1007/978-3-540-77465-5_13.

[27] Jimenez, D., Perez-Uribe, A., Satizabal, H., Barreto, M., Van Damme, P., Tomassini, M., 2008., A Survey of Artificial Neural Network-Based Modeling in Agroecology, in Soft Computing Applications in Industry. Prasad B (ed), p247. Springer-Verlag, Berlin. https://link.springer.com/chapter/10.1007/978-3-540-77465-5_13

[28] United Nations, New York, 2019. Global Sustainable Development Report 2019: The Future is Now – Science for Achieving Sustainable Development. 24797GSDR_report_2019.pdf (un.org).

This situation calls for profound transformations in both consumption and production[29] (HLPE, 2020), in terms of patterns and volumes as well as energy consumption and related practices. Caron et. al. (2018)[7] indeed calls for a profound transformation of food systems that should include four components:

- The consideration of climate change concerns;
- The promotion of healthy and sustainable consumption patterns, including diet change towards eating balanced diets featuring plant-based foods with lower-emission proteins and lower animal-sourced food to produce sustainably in low greenhouse gas emission systems[30, 31], and including the reduction of food loss and waste[31, 32];
- The contribution to the viability and sustainability of ecosystems, including soil health and better fertilisation practices; and
- A renaissance of rural territories.

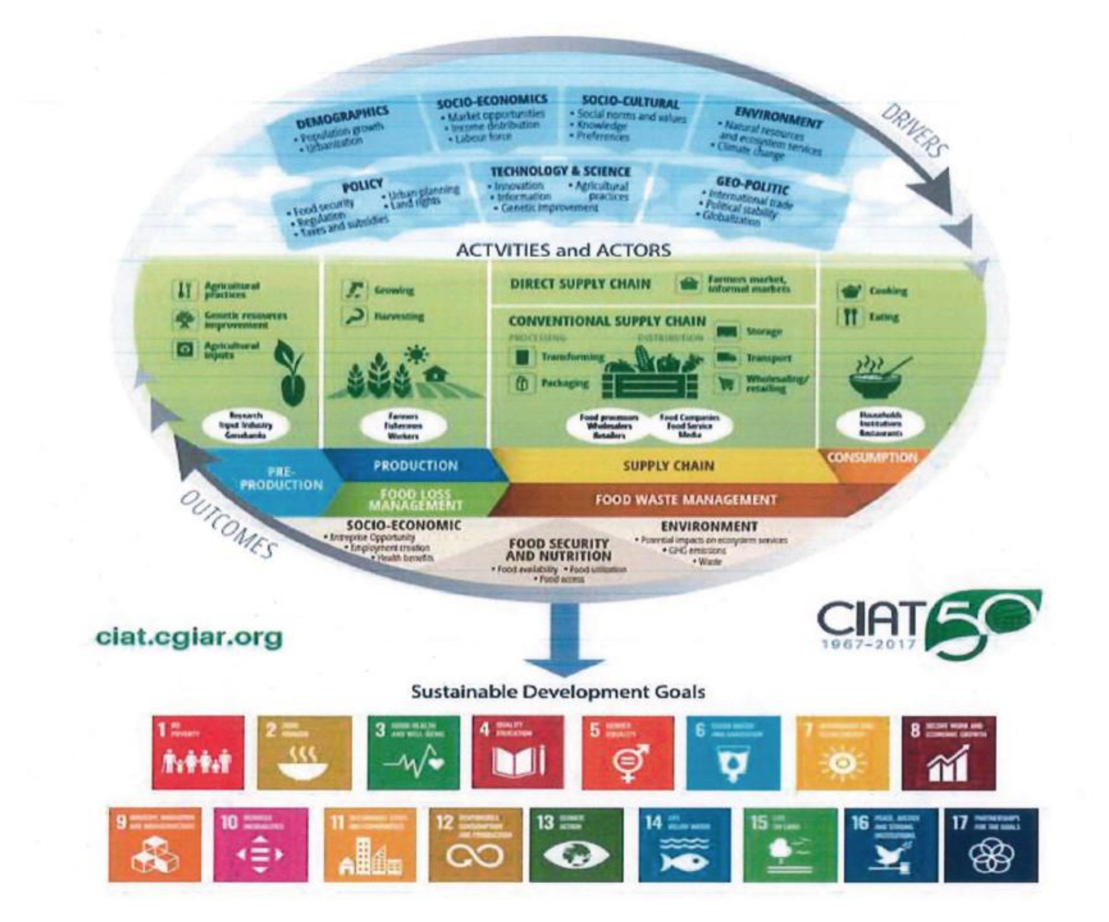

Fig. 1.5. An Interpretation of the Food and Agriculture System illustrating Drivers, Activities, Actors and Outcomes. All elements of growing, harvesting, storing, processing, distributing, consuming and managing the food and agriculture system are encompassed by UN's Sustainable Development Goals (SDGs). Adapted from CIAT, International Center for Tropical Agriculture[33]

Author: Norman R. Scott (member of the group of authors for this chapter), and R. Paul Singh https://www.nae.edu/276571/Guest-Editorss-Note-Science-and-Engineering-to-Transform-the-Food-and-Agriculture-System-for-the-Future

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[29] HLPE. (2020). Food Security and nutrition building a global narrative towards 2030. Vol. 15. High Level Panel of Experts on Food and Nutrition of the CFS-Committee on World Food Security. (pp. 112). Retrieved from https://www.fao.org/3/ca9731en/ca9731en.pdf

[30] HLPE. 2016. Sustainable agricultural development for food security and nutrition: what roles for livestock? A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

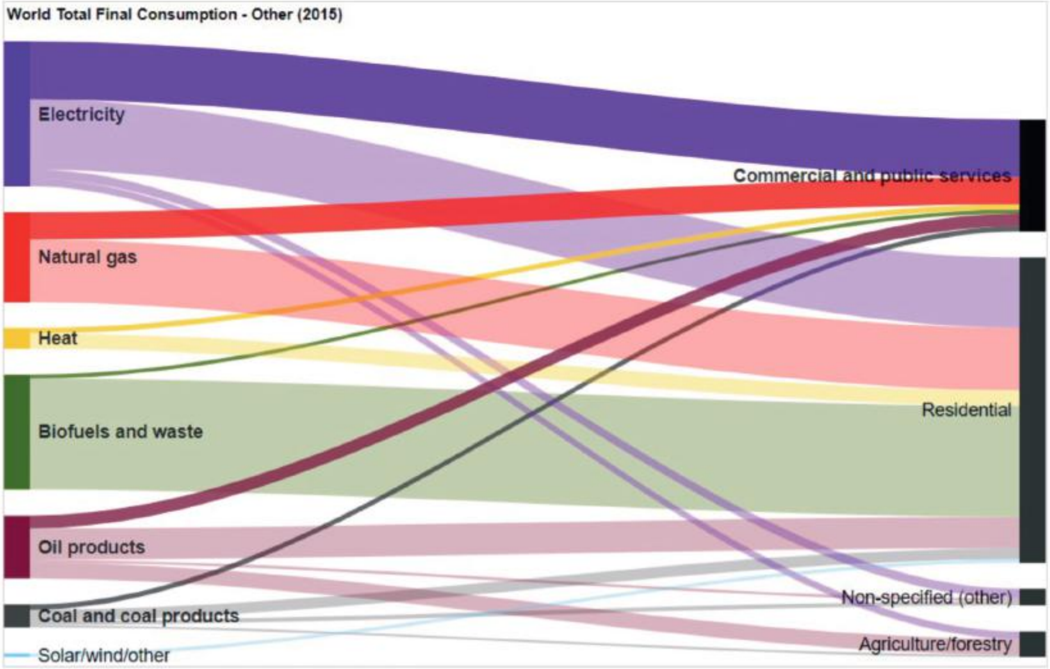
[31] IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]..

[32] HLPE, 2014. Ibid.; IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

[33] CIAT, 2017. https://ciat.cgiar.org/about/strategy/sustainable-food-systems.

2.3. Energy sources ‘fuelling’ the current FAS

The FAS is both a provider and a consumer of energy and the relationship between biofuels and food security is especially challenging. Despite the rapid and intense increase in energy consumption at the production stage, the share in world energy consumption remains marginal, compared to other sectors (*Fig. 1.6.*). *Fig. 1.7.* shows that approximately a 25% of total energy use in High GDP countries occurs in the production stage, 45% in food processing and distribution, and 30% in retail, preparation and cooking in the developed world (IRENA and FAO, 2019). As illustrated by *Fig. 1.8.*, the amount of energy consumed for preparation and cooking may vary tremendously from one country to another. It should be noted that global FAS is becoming more energy intensive in the sectors of processing, packaging, retail and distribution where emissions are growing in some developing countries. Refrigeration and packaging, each contribute about 5% of global food-system emissions[34]. However, emissions can vary substantially by product within the food supply chain.



Data too small to be presented on this graph can be found here.
Data Source: IEA (2018), "World energy balances", *IEA World Energy Statistics and Balances* (database). http://dx.doi.org/10.1787/data-00512-en (Accessed January 2018)

Fig. 1.6. World total energy consumption by the different sectors (IEA, 2018). Reproduced with permission

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[34] FAO. 2021. Food systems account for more than one third of global greenhouse emissions. Rome, Italy: United Nations. http://www.fao.org/news/story/en/item/1379373/icode/.

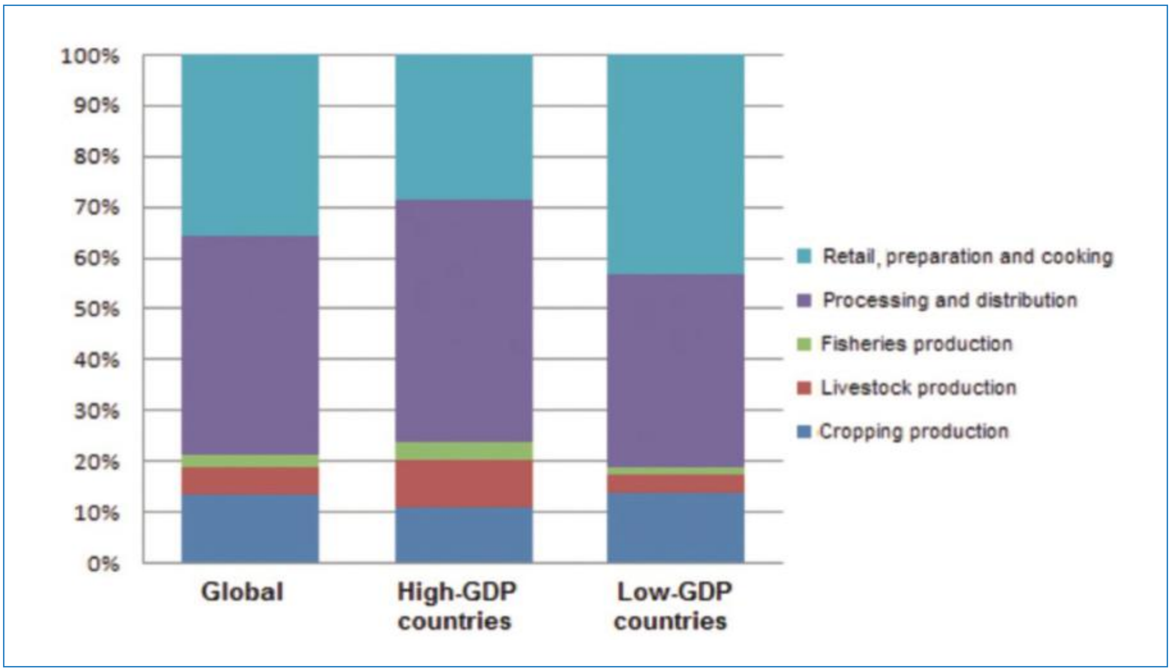

Fig. 1.7. Distribution of shares of end-use total energy across the food supply chain for global consumption (2.64 x 10^{12} kWh) and high-GDP (1.39 x 10^{12} kWh) and low-GDP (1.25 x 1012 kWh) FAO (2011)[35] Energy smart food for people and climate, Issue Paper. Food and Agriculture Organization of the United Nations. Reproduced with Permission. https://www.fao.org/3/i2454e/i2454e.pdf

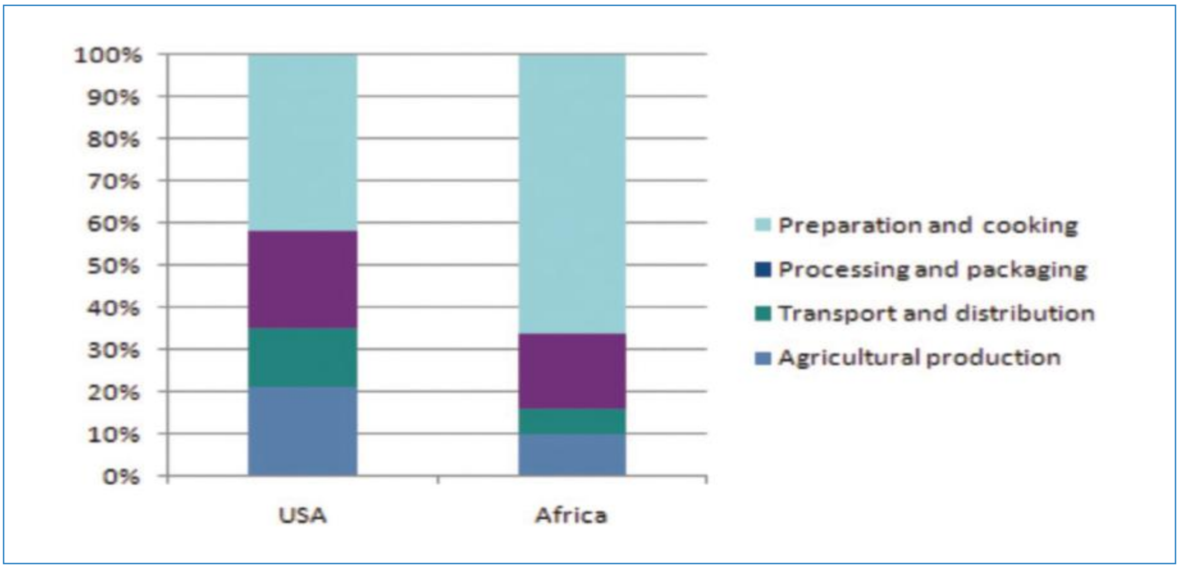

Fig. 1.8. High-GDP and low-GDP differences in energy inputs in the food supply chain. FAO (2011)[35] Energy smart food for people and climate, Issue Paper. Food and Agriculture Organization of the United Nations. Reproduced with Permission. https://www.fao.org/3/i2454e/i2454e.pdf

With the exception of subsistence farming, that depends on human labour and animal power, fossil resources account for roughly 80% of the total global energy consumption for the FAS. For example, in the United States of America, about 93% compared to 86% for the country as a whole of the agri-food chain energy consumption was attributed to fossil fuels in 2007, compared to 86% in nationwide energy utilisation[36].

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[35] FAO. 2011. Global food losses and food waste: Extent, causes, and prevention, Rome, Italy: United Nations. http://www.fao.org/3/mb060e/mb060e00.htm

[36] C Canning, P., Rehkamp, S., Waters, A., & Etemadnia, H. 2017. The role of fossil fuels in the US food system and the American diet. USDA Economic Res. Rept. #224, Jan 2017.

Fig. 1.9. illustrates the points along the agri-food chain where interventions can take place to improve energy efficiencies and the implementation of new technologies. One traditional key renewable component in the energy supply of the food and agriculture sector is biomass energy (via biogas production from agriculture and forestry residues). It is used for heating, vehicular operation, and electricity supply (fed to the national grid or from stand-alone off-grid/mini-grid systems). Other renewable sources like wind, solar, hydropower and geothermal forms, vary by country (depending on national renewable energy policies and on the availability of the respective sources).

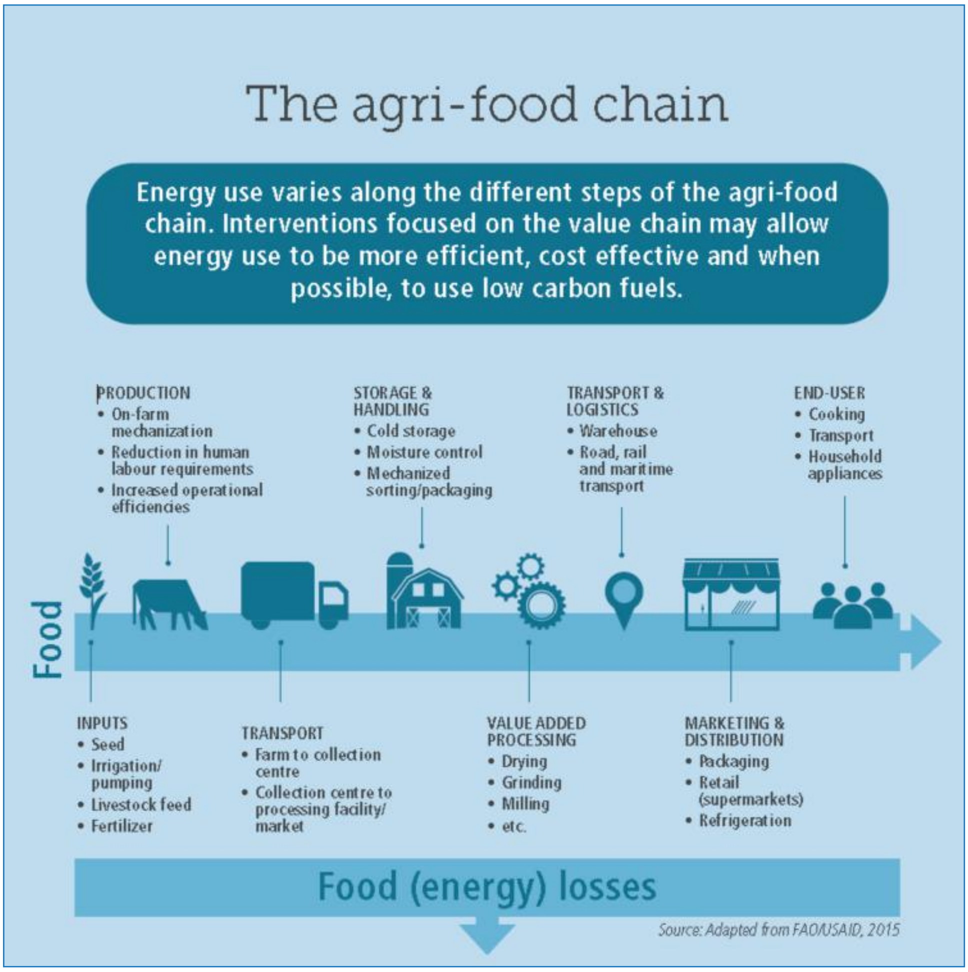

Fig. 1.9. Energy ports along the food-agriculture sector supply chain
Source: Tweet Food and Agriculture Organisation
“Adapted from FAO/USAID, 2015”
https://twitter.com/fao/status/987069593238851585

Over the past three decades, there has been a 15% increase in average global GHG emissions as a result of energy use, and within Africa, Asia and Latin America increases of up to 50%[37]. As noted, the American FAS is driven almost entirely by non-renewable energy sources and accounts for approximately 11% of the total energy consumption in the United States[38]. About 60% of this energy is consumed directly via the use of gasoline, diesel, electricity, and natural gas, while the rest of it (about 40%) is consumed indirectly as it is due to the production of fertilisers and pesticides.

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[37] FAO. 2022 Agrifood chains I Energy. www.fao.org/energy/agrifood-chains/en/

[38] C Canning, P., Rehkamp, S., Waters, A., & Etemadnia, H. 2017. The role of fossil fuels in the US food system and the American diet. USDA Economic Res. Rept. #224, Jan 2017. https://www.ers.usda.gov/webdocs/publications/82194/err-224.pdf..

3. Technologies and their potential for decarbonisation

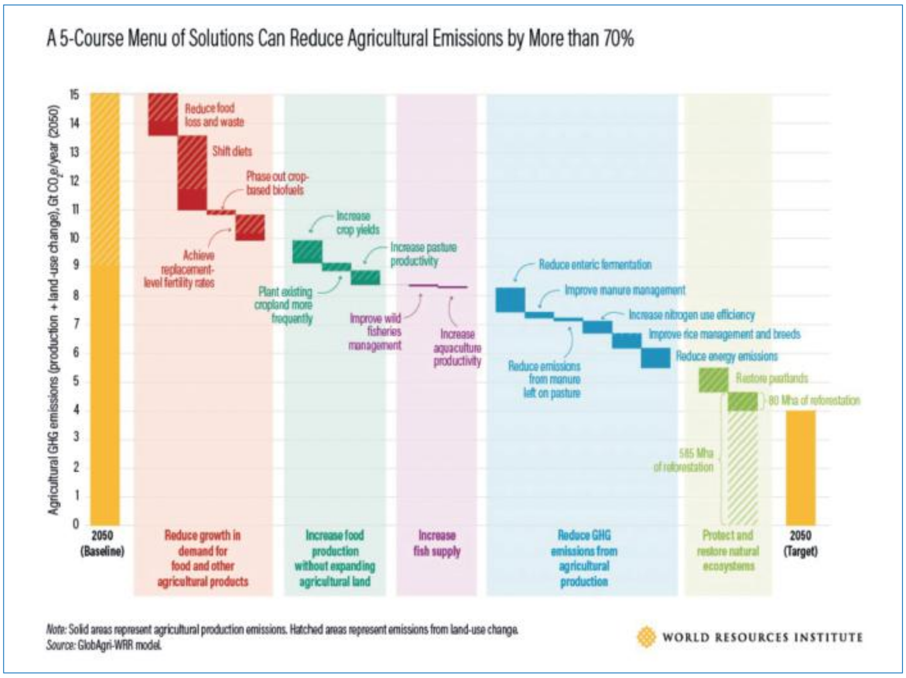
The FAS is a multiple input-multiple output (MIMO) energy and food production system, i.e. a system of systems. Many strategies are available to adapt agriculture, water, food, energy, and the environment nexus and to make it sustainable. They may rely on technologies that relate to consumption, to production and processing, to the optimisation of resources, including new modes of circular bioeconomy and soilless or lab-grown production approaches, such as vertical farms, insect farming or the cell factory. They may also rely on the application of new tools of computer science combined with synthetic biology that makes it possible to contribute to decarbonisation, while envisaging simpler, cheaper production with limited use of agrochemicals, less land, less water, and better yields than in conventional production. It is also noted that the food and agriculture system of production was historically land based. Food engineering was derived from it. With the evolution of new and emerging synthetic biologically derived foods, however, chemical engineering has taken on a heightened role in these new advances[39, 40].

Beyond the questions of consumer acceptability of these unconventional foods and confirmation of environmental, ethical, social, and political implications, numerous hurdles remain to be addressed. These include, for example, the selection and improvement of adapted strains, varieties or species, and the development and standardisation of new and disruptive foods. These hurdles go along with controversies regarding food safety and health, environmental impact (particularly in terms of energy balance between consumption and production), and finally the economic, ethical, social, societal, and regulatory consequences.

Below are some examples that illustrate the diversity of such technologies and some of the questions related to their application and implementation.

3.1. Reducing emissions and shifting diets through technology

As shown in *Fig. 1.10.*, reducing growth in demand for food and other agricultural products would contribute to minimising one third of FAS GHG-related emissions. The figure presents a suite of best practice solutions, behaviour change and policy options to accomplish significant reductions in emissions.


A 5-Course Menu of Solutions Can Reduce Agricultural Emissions by More than 70%

Note: Solid areas represent agricultural production emissions. Hatched areas represent emissions from land-use change.
Source: GlobAgri-WRR model.

Fig. 1.10. Items suggested to reduce emissions within the production component of the FAS illustrating existing best practices, behaviour change and possible policy options [41]

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[39] Hefft, D. I., & Higgins, Śeamus. 2021. Food industry and engineering—Quo vadis? Journal of Food Process Engineering, 44(8). https://doi.org/10.1111/jfpe.13766;

[40] Hefft, D. I., & Higgins, Śeamus. 2022. Re-engineering the Food Industry: Where Do We Go from Here? In C. Hong & W. W. K. Ma (Eds.), Applied Degree Education and the Future of Learning. Springer. https://doi.org/10.1007/978-981-16-9812-5_2

[41] World Resources Institute. 2019. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2025. Final report. July 2019; Chapter 33, Page 427, Reproduced with Permission. https://www.wri.org/research/creating-sustainable-food-future

The IPCC (2022)[42] states that there is medium confidence that shifting toward sustainable healthy diets would have a technical potential in the full value chain including the saving of 3.6 (0.3-8.0) $GtCO_{2e}$/yr of which 2.5 (1.5-3.9) $GtCO_{2e}$/yr is viewed as plausible based on a range of GWP_{100} value for CH_4 and N_2O. When accounting for diverted agricultural production only, the feasible potential is 1.7 (1 – 2.7) $GtCO_{2e}$/yr. A shift to more sustainable and healthy diets is generally feasible in many regions. However, the potential varies across regions as diets are location- and community- specific, and may thus be influenced by local production practices, technical and financial barriers and associated livelihoods, everyday life and behavioural and cultural norms around food consumption.

3.2. Reducing food loss and waste

The issue of global food losses and waste (FLW) is receiving increased attention[43]. *Fig. 1.11.* illustrates that between about 30 to 40% of food produced for human consumption – approximately 1.3 billion tons per year – is either lost or wasted globally. Clearly reduction in FLW will minimise the amount of food needed to feed the growing global population, improve food security and reduce the environmental footprint of food systems.

FLW refers to the edible parts of plants and animals produced for human consumption that are not ultimately consumed. Food loss occurs at the preharvest stage, during harvesting, through spoilage, spilling or other unintended consequences due to limitations in agricultural infrastructure, storage, and packaging[44]. Food waste typically takes place at distribution (retail and food service) and consumption stages in the food supply chain and refers to food appropriate for human consumption that is discarded or left to spoil[45].

Interestingly, food waste is greatest in the developed countries while losses are greatest during harvest and postharvest stages for developing countries.

It is important to note that consumer food waste alone has a greater carbon, GHG, land-use, water, nitrogen, or energy footprint than a similar mass of postharvest loss excluding consumer waste. This is due to the inclusion of transport, packaging, processing, distribution, and preparation at home, all of which is finally “embedded” in consumer waste. Similarly, on average, energy “waste” from consumer waste alone is equivalent to eight times that resulting from postharvest loss where consumer waste is not included[46].

Options that could reduce FLW include: (i) investing in harvesting and postharvesting technologies in developing countries, (ii) improved practices in production and postharvest, (iii) behavioural change by businesses and consumers, (iv) improved coordination in the supply chain, as well as enhanced relationships with other actors, (v) improvement in food processing and valuing food by-products, and (vi) development of new policies[47].

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[42] IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

[43] NASEM. (National Academies of Sciences, Engineering, and Medicine). 2019b. Reducing impacts of food loss and waste: proceedings of a workshop. Washington, DC. The National Academies Press. https://doi.org/10.17226/25396

[44] P Parfitt, J., Barthel, M. & Macnaughton, S. 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554): 3065–3081.

[45] HLPE, 2014. ibid

[46] Dobbs, R., Oppenheim, J., Thompson, F., Brinkman, M., Zornes, M. 2011. Resource revolution: meeting the world’s energy, materials, food, and water needs. McKinsey Global Institute (https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/resource%20revolution/mgi_resource_revolution_full_report.pdf).

[47] HLPE, 2014. Ibid

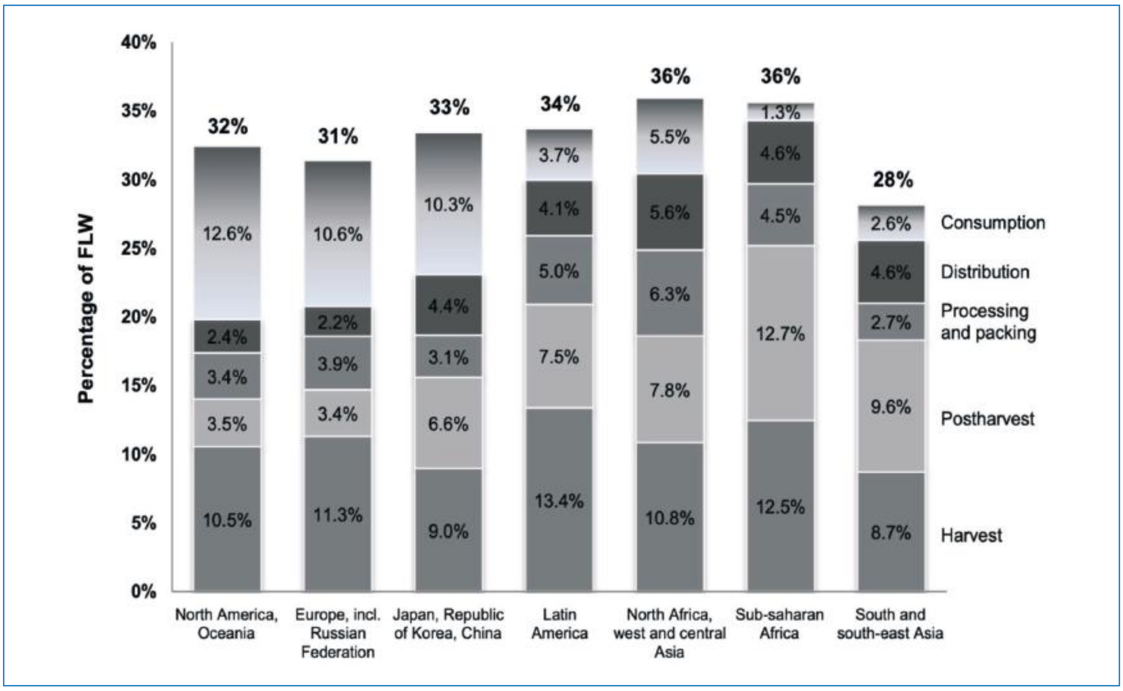

Fig. 1.11. Distribution of FLW along the food chain in the different regions of the world (HLPE, 2014)[45] HLPE Report 8, 2014: Food losses and waste in the context of sustainable food systems. A report by The High Level Panel of Experts on Food Security and Nutrition, June 2014, Page 27, Reproduced with permission. https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-8_EN.pdf

The IPCC (2022) estimates, with medium confidence, that reduced FLW has a large global technical mitigation potential of 2.1 (0.1-5.8) $GtCO_{2e}$/yr including savings in the full value chain using GWP_{100} and a range of IPCC values for CH_4 and N_2O. They suggest potential plausible values as 3.7 (2.2-5.1) $GtCO_{2e}$/yr.

3.3. Valuing new food resources through technology

Global meat consumption is estimated to increase 3% per year to 2040[48, 49]. However, several groups[49, 50] forecast major changes in the conventional animal-agriculture system, with foods being engineered at the molecular level leading to at least 50% less conventional meat and dairy consumption by 2040.

Alternatives to animal-sourced proteins increasingly open and broaden avenues for exploration, particularly so in developed countries where meat has a strong negative impact (*Fig. 1.2.*) in terms of GHG emissions and health[51, 52]. More generally, landless food systems have gained traction during the last decade. We are witnessing significant new biological/biochemistry efforts aimed at creating food from plants or animal cells from the 'bottom up'. Three technologies are characterised as: (i) plant-based alternative foods, (ii) cell-cultured/cultivated foods, and (iii) 3D printed foods. Because they use biochemical building blocks from proteins, carbohydrates, fats, and oils from plants and animals, it is a 'new' agriculture.

While much hype has been on synthetic burgers[53] there has been substantial advancement in other alternative foods, such as eggs, fish, shrimps, milk, yogurt, chicken nuggets, and chicken tenders to mention a few of them. The objective of synthetic biology is to develop food products that mimic traditional foods with significant benefits. Such benefits may be: (i) a production environment unaffected by weather/extreme weather;

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[48] FAO. 2011. Energy-Smart Food for People and Climate Issue Paper Rome: Food and Agriculture Organization. https://www.fao.org/3/i2454e/i2454e.pdf; FAO. 2011. Global food losses and food waste: Extent, causes, and prevention, Rome, Italy: United Nations. http://www.fao.org/3/mb060e/mb060e00.htm;

[49] A.T. Kearney.2020. How Will Cultured Meat and Meat Alternatives Disrupt the Agricultural and Food Industry? https://www.kearney.com/documents/291362523/291366693/When+consumers+go+vegan%2C+how+much+meat+will+be+left+on+the+table+for+agribusiness+%282%29.pdf/fe61e117-356c-6f4e-2fbe-079dab3e5647?t=1608631513000 .

[50] Tubb, C., and Seba, T. 2019.Rethinking food factory: The next generation indoorand agriculture 2020-2030: The second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming. www.rerhinkx.com.

[51] HLPE. 2016. Sustainable agricultural development for food security and nutrition: what roles for livestock? A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-10_EN.pdf;.

[52] FAO. 2006. Livestock's long shadow. Environmental issues and options, by H. Steinfeld, P. Gerber, T. Wassenaar, V. Castel, M. Rosales & C. de Haan. Rome. 464 p.

[53] Purdy, C. 2020. Billion Dollar Burger. Penguin Random House. 252 p.

(ii) year-round production; (iii) shortened growing cycles and higher yields; (iv) reduction in land and water use; (v) lower food loss and waste; (vi) shorter supply chains, local access compatible with urban settings; (vii) reduction or elimination of pesticides and antibiotics; (viii) reduction of GHG emissions; (ix) reduction in water pollution; (x) potential for enhanced micronutrients, and (xi) removal of animal welfare concerns (growing conditions and slaughter).

However, there are potential uncertainties and questions, such as: (i) high capital cost; (ii) timeline to market; (iii) in some cases, high energy consumption; (iv) consumer acceptance; (v) concern about food quality and safety, particularly nutritional content and presence of growth hormones; (vi) price to consumers, (vii) potential contamination; (viii) impact and possible detrimental effect for small farmers and for employment; (ix) proprietary nature of processes; (x) unproven technology, and (xi) whether these new landless systems benefit large-scale economies to the detriment of markets for small farmers[54, 55 , 56].

Sustainability is critical to any future food system and is a driving force for these alternative food systems. In broad terms, they seek to develop foods that impose less environmental impact, enhance human health, and reduce the ethical implications of traditional animal-agriculture production, particularly for meat.

It should also be noted that food cost to the consumer is a crucial issue for any new product to be successfully adopted. Over the past 5 to 10 years, numerous entrepreneurs, start-ups, and food companies have created alternative foods that are already in the marketplace. In many cases, the price to consumers, at present, is higher than equivalent traditional foods, but the difference has decreased over time. As these emerging alternative products are improved, it is possible that cost to the consumer will be reduced to be comparable or even less.

3.3.1. Plant-based alternative food

Globally the food and agricultural system is estimated, as previously mentioned, to generate around 1/3 of total GHG emissions with 71% from agriculture and related land use and land use change[57]. The opportunity for plant-based alternatives to substantially reduce environmental impacts was determined in a comparative study (Life Cycle Assessment-LCA) of the *Beyond Burger* and a U.S. beef burger (quarter pounder) by the Center for Sustainable Systems at the University of Michigan[58]. The selected parameters were GHG emissions, cumulative energy use, water use, and land use. The comparison was made to an LCA study by the National Cattleman's Beef Association[59]. For the *Beyond Burger* system the results showed 90% less GHG emissions, with 46% less energy, 99% less water and 93% less land use. *Impossible Foods* also commissioned a study (Khan et.al., 2019)[60] which found that the *Impossible Burger* uses 96% less land, 87% less water and 89% less global warming potential than a quarter pound beef burger. Independent LCA studies would be beneficial, given the rapidly changing ingredients being used to create plant-based meat alternatives.

Plant-based protein sources (legumes and cereal grains) are an important choice for both the vegetarian and traditional meat consumer. However, challenges remain for developers of plant-based proteins to deliver a healthy, nutritionally safe, tasty flavour, texture, and appearance (colour) comparable to traditional products. Comparisons yield a mixed story because plant-based meats provide about the same calories as traditional meat with more sodium, more potassium (which helps eliminate sodium), no cholesterol, more iron, more B vitamins, more calcium, and more saturated fat. Thus, there is a need to assess whether plant-based protein would be any less safe or safer than traditional meat and of similar nutritional quality.

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[54] Purdy, C. 2020. Billion Dollar Burger. Penguin Random House. 252 p Purdy, 2020; NASEM, 2019; He, C., Zhang, M., Fang, Z. 2019. 3D Printing of food: Pretreatment and post- treatment of materials. Critical Reviews in Food Science and Nutrition, 60(14):2379-2392 https://doi.org/10.1080/10408398.2019.1641065.

[55] NASEM. (National Academies of Sciences, Engineering, and Medicine). 2019a. Innovations in the Food System: Exploring the Future of Food. Proceedings of a Workshop. National Academies Press. Washington, DC http://nationalacademies.org/hmd/Activities/Nutrition/FoodForum/2019-AUG-07

[56] He, C., Zhang, M., Fang, Z. 2019. 3D Printing of food: Pretreatment and post- treatment of materials. Critical Reviews in Food Science and Nutrition, 60(14):2379-2392 https://doi.org/10.1080/10408398.2019.1641065

[57] Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, E, Tubiello, E., Leip, A. 2021. Food systems are responsible for a third of global anthropogenetic GHG Emissions. Nature Food, 2, 198–209. https://doi.org/10.1038/s43016-021-00225-9.

[58] Heller, M., Keoleian, G. 2018.Beyond Meat's beyond burger life cycle assessment: A detalled comparison between a plant-based and animal-based protein source. Report No.CSS18-10. Center for Sustainable Systems, University of Michigan, Ann Arbor 1-38..

[59] Thoma, G., Putman, B., Matlock, M., Popp, J., English, L. 2017. Sustainability Assessment of U.S. Beef Production Systems. University of Arkansas Resiliency Center. https://scholarworks.uark.edu/rescentfs/3.

[60] Khan, S., Loyola, C., Detting, J., Hester, J. 2019. Comparative environmental LCA of the Impossible Burger with conventional ground beef burger. Report prepared by Quantis for Impossible Foods. https://assets.ctfassets.net/Hv516v5tsj/43xFx74UoYku640WSF3t/cc2136148ee80fa2d8062ef0012ec56/impossible foods comparable LCA.pdf.

3.3.2. Cell-cultured food

Cell-cultured meat, also known as cultivated meat, has advanced at a rapid pace over the past 20 years. The concept, although relatively simple, uses animal cells nurtured within a bioreactor to produce food that is designed to mimic meat products[61]. Compared to plant-based protein where protein is extracted from plants, cell-based meat is created from cells extracted from animals and grown in a culture. Specifically, a small piece of fresh muscle, obtained by biopsy, from a living animal is stimulated by a combination of mechanical and enzymatic methods to produce stem cells[62].

Using culturing methods, the adult stem cells (called satellite cells), in the presence of relatively high serum concentrations, divide, thus leading to multiplying populations. Tissue engineering methods are then used to differentiate these expanded cells into muscle and fat tissue, which leads to the generation of a cultured meat product closely resembling conventional meat. A recent study suggests that it may be possible to grow cultured meat with much less dependence on animals by using a soy-based scaffold to support muscle cells and form a meat-like 3D-cell structure[63].

A Life Cycle Assessment (LCA)[64] and a (TEA) techno-economic assessment[65] modelled future large-scale cell-cultured meat production facilities and showed reduced overall environmental impacts and the potential to be cost-competitive with conventional meat by 2030. These are the first reports using data collected from active companies (more than 15) in the chain.

The LCA shows cell-cultured meat is about 3.5 times more efficient (feed conversion ratio) than poultry which is the most efficient system of conventional meat production. The LCA in comparison with traditional meat includes the use of renewable energy in which case there is a reduction of 17-92% in GHG emissions, 63-95% in land use and 51-78% in the use of water depending on the respective conventional animal system. Thus, relative comparisons with conventional meat depend on the type of systems used for generating energy (i.e., decarbonised, and renewable) and the specific animal production system. In addition, exploring such avenues raises some ethical, cultural, and religious issues.

3.3.3. 3D-printed food

The combination of robotics and software has entered the realm of food manufacturing in the form of 3D printing[66, 67, 68, 69] 3D printing technology is a novel approach which can create complex geometries, tailored textures, and nutritional contents. The 3D technology can provide 'customised food' to meet special dietary needs as well as mass customisation.

In the 3D-printing process, food ingredients are placed in cartridges, and the product is created layer by layer by a controlled robotic process, like the 3D printing of non-food items. The technology has been employed to use tissue engineering in order to create meat and other food alternatives. The 3D technology has also been employed at the home scale to create 'designer' foods. Depending on the specific food, ingredients can range from processed components (sauces, dough, etc.) to more elemental ingredients such as sugars, proteins, fats, and carbohydrates[69]. Some foods may require further processing, such as some form of cooking or storage. A significant challenge is to link material properties and structure to printing process variables to obtain the desired 3D-printed product. The parameters of control are those relating to the printer and those controlling the food-relevant parameters. Thus, it seems not to be a great stretch to infer that 3D printing will lead to designer and specialised food products. The 3D-printing process compresses the value chain to a highly local

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[61] Boler, D., Martin, J., Kim, M., Krieger J., Milkowski, A., Mozdziak, P., Sylvester, B. 2020. Producing food products from cultured animal tissues. www.cast-science.org/wp-content/uploads/2020/04/QTA2020-1-Cultured-Tissues-1.pdf.

[62] Post, M. 2013. Cultured beef: Medical technology to produce food. J. Food and Agriculture. 94(6):1039 1041. Doi:10.1002/jsfa.6474

[63] Young J., Skivergaard, S. 2020. Cultured meat on a plant-based frame. Nature Food 1, 195. https://doi.org/10.1038/s43016-020-0053-6.

[64] CE Delft. 2021a. LCA of cultivated meat: Future projections for different scenarios. https://www.cedelft. cuen/publications/2610/lca-of-cultivated-meat-future

[65] CE Delft. 2021b. TEA of cultivated meat: Future projections of different scenarios. https://www.cedelft.eu.en/publications/2609/tea-of-cultivated-meat-future.

[66] Dankar, I., Haddarah, A., Omar, F., Sepulcre, F., Pujola, M. 2018. 3D Printing technology: The new era for food customization and elaboration. Trends in Food Science & Technology.75(231-242). https://doi.org/10.1016/j.tifs.2018.03.018;

[67] Yang, F., Zhang, M., Bhandari, B. 2017.Recent developments in 3D food printing. Critical Reviews in Food Science and Nutrition, 57:14, 3145-3153. doi:10.1080/10408398.2015.1094732;

[68] He, C., Zhang, M., Fang, Z. 2019. 3D Printing of food: Pretreatment and post- treatment of materials. Critical Reviews in Food Science and Nutrition, 60(14):2379-2392 https://doi.org/10.1080/10408398.2019.1641065.

[69] Severini, C., Derossi, A., Azzollini,D. 2016. Variables affecting the printability of foods: Preliminary tests on cereal-based products. Innovative Food Science and Emerging Technologies. 38(281-291). http://dx.doi.org/10.1016/j.ifset.2016.10.001

system made of inputs (ingredients), a single controlled process (the 3D printer) and a single output (the food product) and it can thereby possibly reduce energy and GHG emissions across the value chain.

3.3.4. Advanced Greenhouses and Vertical Farms

The concept of growing plants in environmentally controlled areas can be traced back to Roman times[70]. The concept of the greenhouse, as we have come to know it today, began in the Netherlands and then England in the 17th century. They evolved from simple row covers to very large structures in the 1960's when materials such as polyethylene films, aluminium extrusions, special galvanised steel, and PVC tubing became available for various structural support frames.

The advanced greenhouse is defined here as a greenhouse with a highly controlled environment, high automation under computer control and uses a soilless growing medium, a hydroponic solution. The controlled environment for plant production consists of an intensive assessment of the environment by numerous sensors to measure and monitor such parameters as: temperature, pH, relative humidity, dissolved O_2 in nutrient solution, electrical conductivity for dissolved salts in nutrient solution, CO_2 of inside air, and light intensity from the sun and supplemental lighting, and PAR (photosynthetic active radiation) in $mol/m^2/d$. Quality and optimum plant growth is dependent on plants getting an optimum daily quantity of PAR ($mol/m^2/d$). If the daily PAR is not provided by the sun, the computer will implement supplemental lighting to meet the desired value.

An advanced greenhouse consists of a complete system from the germination of seeds to the finished product. Typically, the seed is planted in a fibrous material such as a Rockwool cube to germinate. Following germination, the cubes are inserted into a material (like Styrofoam) to float on the surface of the nutrient solution until fully mature. Temperature will be controlled typically by mechanical fan ventilation under computer control of air flow by managing air intake openings. Where appropriate, evaporative cooling may be used to provide cooling. The addition of CO_2 can be used to increase plant growth. Shading material can be used to reduce excessive solar energy and movable insulation to reduce heat loss at night respectively. Beyond the controlled thermal technologies and growing environment, the advanced greenhouse will include a significant automation for the handling of materials, including the use of robots[71].

Based on recent developments in advanced greenhouses, the Vertical Farm (VF) uses the vertical dimension (*Fig. 1.12.*) to grow plants in stacked layers thereby greatly increasing the amount of product grown per unit area[72, 73, 74, 75]. Like for the advanced greenhouse, the growing environment in a vertical farm is closely controlled for temperature, humidity, ventilation, and the properties of the nutrient solution, including the introduction of robotics. Five reasons to take vertical farms seriously are that: the effect of weather and weather extremes is avoided; water usage is largely reduced, by as much as 95%; plant yields are high, and the growing cycle is short; food loss is lower; supply chains are shorter because VFs can be located in urban areas; and products can be produced year-round[76].

Key challenges for VFs are high capital and energy costs. The issues of high energy consumption in VFs are due to full artificial lighting (LEDs) and for meeting cooling and humidification loads. More efficient LEDs using LEDS tailored to the light spectrum for the specific crop, rather than the full spectrum, may save electricity. Possibly the residual heat could be used in a surrounding case where a source of heat is needed for a closely located enterprise. Clearly, because of large capital costs and energy requirements, VFs will remain a ‘niche’ system until these issues are resolved. In comparison with advanced greenhouses, where solar energy is utilised and where greenhouses can also be located in urban environments (rooftops and vacant lots for example), VFs would seem to offer uncertain benefits. Efforts to conduct a Life Cycle Assessment of VFs and, in addition, approaches

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[71] Ting, K., Lin, T., Davidson, P.2016. Integrated urban controlled environment agricultural systems. In: Kozai T, editor. LED lighting for urban agriculture. Springer-Science+Business Media, Singapore. p. 18-36 doi: 10.1007/978-981-10-1848-0_2.

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[73] Despommier, D. 2011. The Vertical Farm: Feeding the World in 21st Century. Martin's Press. NY, NY. 293 p.;

[74] Kozai, T. (Editor). 2018. Smart plant factory: The next generation indoor Vertical farms. Singapore: Springer; Kozai, T., Fujiwara K., Runkle, E. 2016. (Editors). 2016. Plant Factory and Greenhouse with LED Lighting.Singapore: Springer.

[75] Kozai, T., Fujiwara K., Runkle, E. 2016. (Editors). 2016. Plant Factory and Greenhouse with LED Lighting. Singapore: Springer.

[76] Pinstrup-Andersen, P. 2017. Is It Time to take vertical farming seriously? 2017. Global Food Security. https://dx.doi.org/10.1016/j.gfs.2017.09.002.

for an integration of VFs into cities are critical to assess the future of VFs. Numerous VFs have been developed and a substantial number, as well, are in the planning stages in the United States of America and Asia. Some of these are conceptualised to include solar energy directly, aquaculture and even livestock production[77].

Fig. 1.12. An example of a vertical farm
Source: Photo by Markus Spiske on Unsplash, free to be reproduced.
https://unsplash.com/fr/photos/9cHVqn9bBpQ

3.4. Improving food supply through technology

3.4.1. Regenerative agriculture / agroecology / organic agriculture

Agricultural management practices that increase soil organic matter in croplands is the focus of much interest. They include (1) crop management, in the form of, for example: high input carbon practices such as adopting improved crop varieties, crop rotation, the use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology; (2) nutrient management, including fertilisation with organic amendments/ green manures; (3) reduced tillage intensity and residue retention; (4) improved water management, including the drainage of waterlogged mineral soils and irrigation of crops in arid/semi-arid conditions, (5) improved rice management (6) and biochar application[78].

The practices referred to as regenerative agriculture and agroecology, as well as organic agriculture, have been drawing much attention recently. These terms have no universal definitions but are frequently described – regenerative agriculture, as “a land management philosophy whereby farmers and ranchers grow food and fibre in harmony with nature and their communities”[79]; agroecology as “the study of relationships between plants, animals, people, and their environment - and the balance between these relationships”; organic agriculture as “a production system that relies on ecosystem management and does not allow the use of synthetic chemical inputs (inorganic fertilizers and pesticides). It relies on ecological processes and natural sources of nutrients (such as compost, crop residues and manure)[80]".

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[77] Kalantari, F., Tahir, O., Lahijani, A., Kalantari, S. 2017. A review of vertical Farming technology: A guide for implementation of building integrated agriculture in cities. Advanced Engineering Forum 24 (76-91),doi.10.4028/www.scientific.net/AEF.24.76

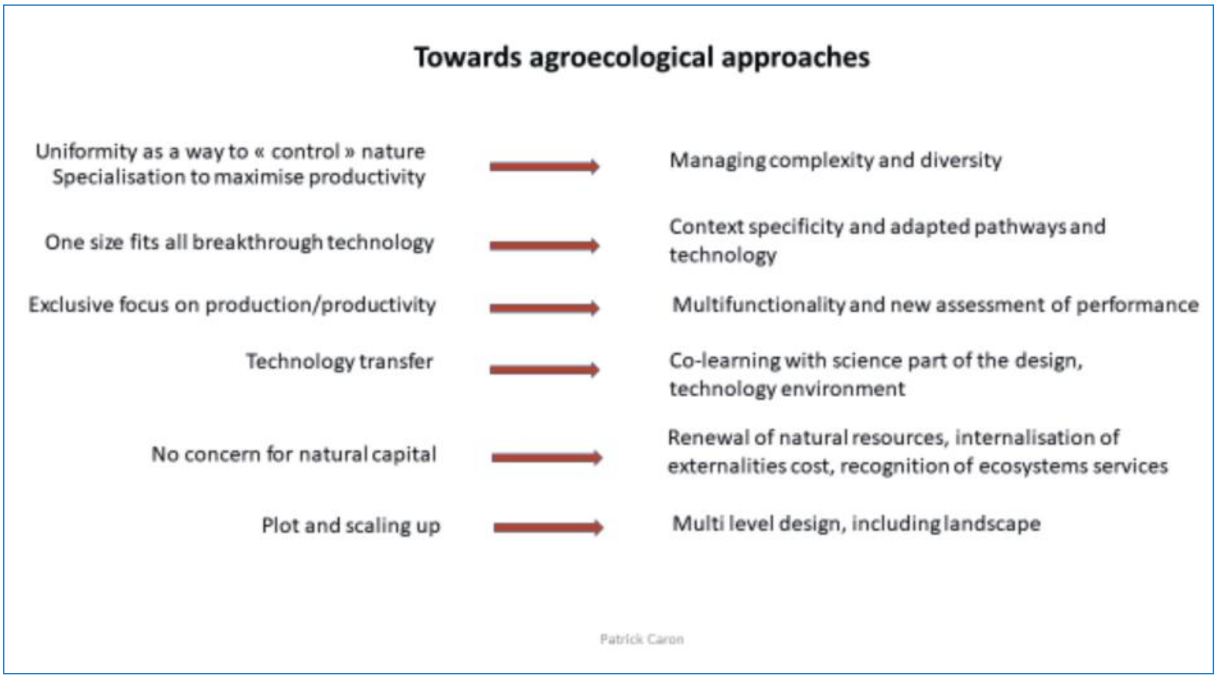
[78] IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses.

[79] NRDC (National Resources Defense Council). 2022. Regenerative Agriculture: Farm Policy for 21st Century. regenerative-agriculture-farm-policy-21st-century-report-pdf.

[80] Page 150 in Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/3/ca5602en/ca5602en.pdf.

Agroecological approaches acknowledge 6 major shifts[81] (see *Fig. 1.13.*). Both regenerative agriculture and agroecology are commonly perceived to advance: no- or minimum-till farming, cover crops, diverse crop rotations, rotating livestock grazing, and a lessened use of fertilisers, pesticides, and herbicides for the purpose of sequestering carbon and promoting a healthy soil. Cropping system diversification has been shown to reduce the negative environmental impacts of soil erosion and nutrient runoff, and reduced cropping inputs while maintaining crop yields[82]. Organic farming can be considered as a form of agroecology and regenerative agriculture because it is guided by similar principles in general, although it is associated with specific regulations. Organic farming is perhaps more noted for its potential co-benefits, such as enhanced system resilience and biodiversity promotion, than for mitigation. While there are similarities across regenerative agriculture and agroecology, there are also important disputes that mainly relate to the polysemy of both terms and to the development models they are supposed to promote, in particular to the respective roles of market and policies[83].

There is general agreement that regenerative agriculture and agroecology practices improve soil health and provide environmental benefits. Some researchers report[84] that regenerative agriculture practices have limited potential to significantly increase soil carbon sequestration. Nevertheless, some corporations have set up a carbon sequestration market (Bayer) and a carbon credit for soil carbon sequestered (Land O'Lakes) intended for farmers. In addition, Cargill, McDonald's, Nestle, Walmart Foundation and other major companies are collaborating with the World Wildlife Foundation on regenerative practices to improve grasslands of the Northern Great Plains of the U.S. It is suggested that, going forward, farmers will need to be paid for environmental services, in particular soil carbon storage. However, this requires an ability to accurately measure soil carbon and quantify change in the field over time in order to assess the effects of differing practices, as well as institutional arrangements to reward practices. Future research is thus needed to find new ways of soil carbon sequestration and gather data through the measurement of soil carbon content in order to develop a global carbon market.



Towards agroecological approaches

Uniformity as a way to « control » nature
Specialisation to maximise productivity → Managing complexity and diversity

One size fits all breakthrough technology → Context specificity and adapted pathways and technology

Exclusive focus on production/productivity → Multifunctionality and new assessment of performance

Technology transfer → Co-learning with science part of the design, technology environment

No concern for natural capital → Renewal of natural resources, internalisation of externalities cost, recognition of ecosystems services

Plot and scaling up → Multi level design, including landscape

Patrick Caron

Fig. 1.13. Towards agroecological approaches[85]

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[81] Caron P., 2021. Agroécologie : saisir les blocages internationaux. In : La transition agroécologique. Quelles perspectives en France et ailleurs dans le monde ? Tome 1. Hubert Bernard (ed.), Couvet Denis (ed.). Paris : Presses des Mines, 131-140. (Académie d'agriculture de France) ISBN 978-2-35671-620-0.

[82] Tamburini, G., Bommarco, R., Wanger, T., Kremen, C., van der Heijden, M., Liebman, and M., Hallin, S. 2020. Agricultural diversification promotes multiple ecosystems services without compromising yield. Sci. Adv.eaba175.

[83] HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/3/ca5602en/ca5602en.pdf.

[84] IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

[85] Caron P. (member of the group of authors for this chapter), 2021. Agroécologie : saisir les blocages internationaux. In : La transition agroécologique. Quelles perspectives en France et ailleurs dans le monde ? Tome 1. Hubert Bernard (ed.), Couvet Denis (ed.). Paris : Presses des Mines, 131-140. (Académie d'agriculture de France) ISBN 978-2-35671-620-0, 2021.

Along with the agroecology discussion, a long-standing debate relates to the opposition between land sparing and land sharing. This was initiated to address the Question of whether it is best to make agriculture more biodiversity-friendly by conserving biodiversity within agricultural landscapes ("land-sharing") or sharply separate the zones managed for biodiversity from those managed for high-intensity agricultural and maximised output (land-sparing). This dichotomy is now disputed as intensification has proved to be a driver for land expansion when strict land tenure regulation is not in place. In addition, and as shown by the HLPE/CFS[86], "there is no single universal answer to this debate, which originated from questions raised at the global level to address agriculture-driven deforestation- and environment-related concerns. At the local level, avenues to address such concerns, including mixed arrangements, and their impact may vary according to specific biological, ecological, and institutional context." Finally, the HLPE/CFS challenges the basic "assumptions underlying this apparent dichotomy. First, in terms of whether conservation friendly agricultural practices are necessarily low-yielding and, second, the extent to which the impacts on biodiversity of chemical-intensive agriculture are confined to the areas where it is practiced."

A specific practice under study in India is the Broad Bed Furrow (BBF) which is proposed to enhance rainfed farming[87]. The goal is to adopt appropriate technology to best manage limited soil moisture in areas of limited rainfall. The BBF system involves the preparation of a broad bed of 90 cm, a furrow of 45 cm and sowing of crop at a row spacing of 30 cm on the bed. The projected benefits are water savings, erosion control, moisture conservation and a channel for drainage in the case of heavy rainfall. Limited results indicated that BBF technology has the potential to increase water productivity for some crops.

Finally, it is noted that the IPCC (2022) states with medium confidence that enhanced soil carbon management of croplands has a global technical mitigation potential of 1.9 (0.4-6.8) $GtCO_2$/yr and in grasslands 1.0 (0.2-2.6) $GtCO_2$.

3.4.2. Nitrogen-use efficiency / optimal nitrogen management

Nitrogen fertiliser plays a critical role in food production globally, but it is also responsible for a variety of environmental problems associated with its loss in various ways. Nitrogen is important for healthy crops, enhancing soil organic carbon, and increasing crop yields. Nitrogen fertiliser is largely, at present, produced using a process called the Haber-Bosch reaction in which hydrogen, primarily from natural gas (via steam reforming - an endothermic reaction), is reacted with nitrogen from air to produce ammonia (NH_3), the basic building block of all nitrogen fertilisers. This process uses a large amount of fossil energy, approximately 70 MJ/kg (19,4 kWh/kg) depending on the respective plant. Energy thus used in production of nitrogen fertilisers is the largest source of fossil fuel consumption in agriculture, with predictions that it will constitute 2% of global energy use by 2050[88]. Although it will vary by the respective production system for N, the largest component of energy use (as much as 30-40%) is that attributed to making synthetic nitrogen fertilisers.

The production of nitrogen fertiliser (see chapter on Chemicals) and its use in agriculture both generate GHGs and comprises the largest source of ammonia, nitrate, and nitrous oxide pollution globally, with severe impacts on ecosystems, human health, and climate change. If yields are to be the same on a global scale, developed Western countries should use less nitrogen fertiliser and poor countries more according to van Grinsven et. al. (2022)[89]. This study looked at meeting the needs of a reliable food supply, but also at the costs associated with the environmental effects of nitrate leaching, soil depletion and ammonia emissions.

Dealing with nitrogen problems in global agriculture requires a holistic nitrogen and food system approach, balancing risks and opportunities for changes in land use and resource security for agriculture, rural livelihoods, dietary choice, and technology advances. The nutrient stewardship principles of the 4Rs (right source of N fertiliser, right rate, right timing application, and right placement) suggest numerous approaches such as renewable electricity-based fertiliser plants, integrated soil and fertility management of cropping systems,

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[86] HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/3/ca5602en/ca5602en.pdf.

[87] Verma, P.D., Parmanand and Tamrakar, S.K. (2017). Effect of broad bed furrow method for rainfed soybean cultivation at Balodabazar district of Chhattisgarh. Internat. J. Agric. Engg., 10(2) : 297-301, DOI: 10.15740/HAS/IJAE/10.2/297-301.

[88] Harpankar, K. 2020. Optimal Nitrogen Management for Meeting Sustainable Development Goal 2. in Science, Technology, and Innovation for Sustainable Development Goals. Editors: Adenle, A., Cheroot, M., Moors, E., and Pannell, D, pg 369-384. Oxford University Press. NY, NY.

[89] Van Grinsven, H.J.M., Ebanyat, P., Glendining, M. *et al.* 2022. Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates | Nature Food , *Nat Food* 3**,** 122–132. Correction: https://www.nature.com/articles/s43016-022-00475-1

biological nitrogen fixation (for example through CRISPR editing), precision agriculture for placement and nanotechnology coatings for time release of N. Specifically, it is necessary to optimise N application in order to minimise environmental effects while maximising plant uptake without significant reduction in yields. It should be noted that farmers also have to meet supply chain specifications, e.g., protein content. Improved crop nutrient management consisting of these practices and others is estimated by the IPCC (2022), with medium confidence, to have a technical potential of 0.3 (0.06-0.7) $GtCO_{2e}$/year.

"Green" ammonia, produced with hydrogen, obtained from water electrolysis, and nitrogen from the air, in an "all- electric" process, might be an alternative to the fossil fuel-based ammonia production. Where stranded wind and solar energy sources (energy capacity exists but cannot be used or sold) are available in agricultural regions, there could be possibilities for regional small-scale all-electric ammonia projects. Another example could be an integration with bioethanol plants by capturing emissions of CO_2 to react with ammonia and thus produce urea, a more easily stored and applied form of nitrogen fertiliser.

3.4.3. Agroforestry

The term agroforestry is applied to land use systems in which perennial woody plants are cultivated on the same area as useful plants and/or livestock[90]. The inclusion of trees or other woody perennials within farming systems is designed to capture the interactive benefits of perennials and/or animals in their use of growth resources (i.e., light, nutrients, water) compared to single-species systems (Lorenz and Lal, 2018)[91]. Lorenz and Lal (2018) classify these systems into agrosilvicultural (crops and trees), silvopastoral (pasture / animals + trees), and agrosilvopastoral (crops + pasture / animals + trees). Agroforestry systems are estimated to cover about 10 million km^2 of agricultural land globally and are most widespread in tropical regions such as Southeast Asia, Latin and Central America, and in the areas of sub-Saharan Africa, where they are often adopted by small land holders. The purpose is to create ecological and economic benefits through the synergy of the individual components (*Fig. 1.14.*).

Trees capture large amounts of atmospheric carbon dioxide (CO_2) during photosynthesis and transfer a fraction of these to the soil, which may be sequestered. Estimates for the carbon (C) sequestration potential above and below ground over a period of 50 years range between 1.1 and 2.2 Pg (1 Pg = 1Gt = 10^{15}g) C/year but these numbers are highly uncertain[91] because of the great diversity of land practices in agroforestry systems. Agroforestry may also enhance biodiversity by creating structural diversity, retreats for animals, as well as water quality benefits. There is however a significant need to develop standard methods and procedures to determine the amount of carbon sequestration from global agroforestry and quantify the system as a low-cost method for environmental benefits.

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[90] Schneider, P., Rochell, V., Plat, K., Jaroski, A. 2021. Circular approaches in small-scale food production. Circular Economy and Sustainability. 1:1231-1255. https://doi.org/10.1007/s43615-021-00129-7.

[91] Lorenz, K., Lal, R. 2018. Agroforestry Systems. In: Carbon Sequestration in Agricultural Ecosystems. Springer, Cham. https://doi.org/10.1007/978-3-319-92318-5_6

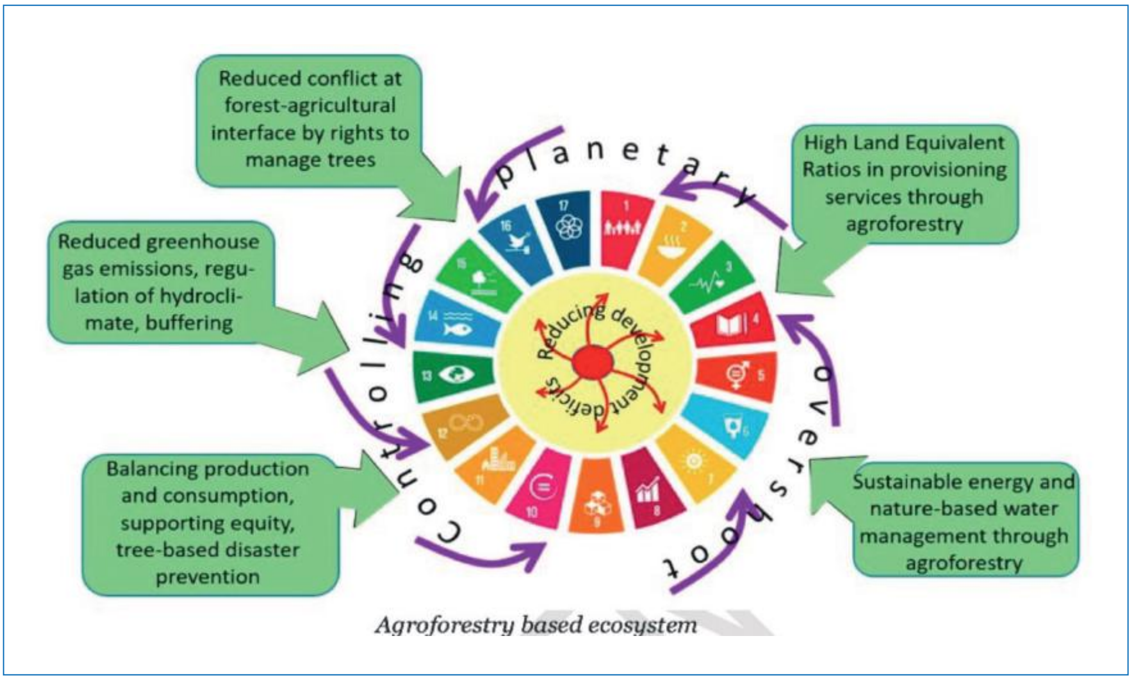

Fig. 1.14. Illustration of agroforestry systems for ecosystem services and economic benefits[92]
Source: Van Noordwijk, M. 2021. Agroforestry-Based Ecosystem Services: Reconciling Values of Humans and Nature in Sustainable Development. Land 2021, 10(7),699
https://www.mdpi.com/2073-445X/10/7/699

3.4.4. Food manufacturing/processing

Global energy demand for food manufacturing and distribution accounts for approximately 45% of the energy consumption of the FAS. Despite the variability of available data for energy demand, depending on the different products and processes, Ladha-Sabur et.al. (2019)[93] have developed a database for energy consumption. They identified general trends on energy consumption owing to manufacturing and transportation, with attention to the UK food system. The most energy intensive food products are powders (i.e., instant coffee and milk powders), fried goods (French fries and crisps), and bread, which involve thermal processes. Hygiene and sanitary requirements also affect water consumption and waste for meat and dairy. It should be noted that packaging is not included in the report by Ladha-Sabur et al. (2019).

Advances in food processing are emerging with a significant potential impact on reducing energy consumption and GHG emissions in food manufacturing through processes such as high-pressure processing[94], cold plasma[95], pulsed electric field[96], ultrasound[97], and microwaves[98]. These processes rely on electricity, thus offering the opportunity to replace traditional processes, which have been based on thermal processes using fossil fuels.

In terms of transportation, there are current movements that advocate for a more decentralised/distributed supply chain supporting local production. However, the environmental benefits of 'local' are mixed. Global environmental assessments, using tools such as LCA to address the whole food chain, are increasingly needed.

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[92] van Noordwijk, M. 2021. Agroforestry-Based Ecosystem Services: Reconciling Values of Humans and Nature in Sustainable Development. Land 2021, 10(7), 699; https://doi.org/10.3390/land10070699

[93] Ladha-Sabur, A., Bakalis, S., Fryer, P., Lopez-Quiroga, E. 2019. Mapping energy consumption in food manufacturing. Trends in Food Science and Technology. 86(270-280) https://doi.org/10.1016/j.tifs.2019.02.034

[94] Huang, H., Wie, S., Lu, J., Shyu, Y., Wang, C. 2016. Current status and future trends of high pressure processing in food industry. Food Control 72(1-8) https://doi.org/10.1016/j.foodcont.2016.07.019

[95] Laroque, D., Seo, S., Valencia, A., Laurindo, J., Carcifi, B. 2022. Cold plasma in food processing: Design, mechanisms, and application. Journal of Food Engineering. 312. https://doi.org/10.1016/j.jfoodeng.110748

[96] Leong, S. and I. Oey. 2019. Pulsed electric fields processing of plant-based foods: An overview. Encyclopedia of Food Chemistry. 245- 254. https://doi.org/10.1016/B978-0-08-100596-5.21653-3

[97] Bhargava, N., Kumar, K., Sharanagat. 2021. Advances in application of ultrasound in food processing, A review. Ultrasonics Sonochemistry. 70. https://doi.org/10.1016/j.ultsonch.2020.105293

[98] Tang, T. 2015. Unlocking potentials of microwaves for foods safety and quality. Journal of Food Science. 80(8) E1776-E1793. https://doi.org/10.1111/1750-3841.12959.

3.4.5. Food storage

Food handling constitutes a large sector of energy consumption in producing food (*Fig. 1.7.* and *1.8.*). This part of the system includes retail, restaurants, packaging, and consumers. In addition, various systems along the food value chain are involved in food storage, thus requiring significant energy. With many crops, on-farm storage is required in order to preserve product quality. The development of efficient and cost-effective solar drying with thermal energy storage systems, to continuously dry agricultural food products, is a viable substitute for fossil fuel in much of the developing world[99] as well as developed world.

The food and beverage sector is a leading source of cooling demand for industrial and transport refrigeration. Producers use refrigeration within the manufacturing process to safely store food products. In developing countries, the lack of refrigerated storage means that postharvest losses may be large. It also means that farmers must sell their products quickly, at market rates. During supply gluts, the inability to store products can have a detrimental effect on farmers' incomes. A start-up based in India has developed a portable cold storage box which runs on solar power, rather than the grid, and is thus unaffected by unreliable power supply. It is also portable, allowing a farmer to rent it to another farmer when it is not in use. At the other end of the spectrum, the largest food manufacturers in the world use high amounts of refrigeration and have typically relied on the use of fossil energy with HFCs (Hydrofluorocarbons) as the refrigerant, which amounts to 20% of total global HFC use. HFCs are a potent GHG[100].

Refrigerated storage can account for up to 10% of the total carbon footprint for some food products when taking into account electricity inputs, the manufacturing of cooling equipment, and GHG emissions from lost refrigerants. A number of approaches can thus be put in place to reduce energy consumption and GHG emissions by: increasing energy efficiency, adding thermal insulation to the storage structure; installing/replacing energy inefficient equipment; eliminating the use of HFCs; and utilising low-carbon electricity, when possible.

3.5. Technology for resource optimisation

3.5.1. Circular food systems

The goal is to design out waste, keep materials in use and in circulation, and regenerate natural systems within the FAS. The concept of circularity originates from industrial ecology, which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances and thus address environmental goals for sustainable development[101, 102, 103]. Under this paradigm, losses of materials and substances should be prevented, and otherwise be recovered for reuse, remanufacturing, and recycling. In line with these principles, moving towards a circular food system implies searching for practices and technology in food production and consumption that minimise the input of finite resources, encourage the use of regenerative ones, prevent the leakage of natural resources (e.g. carbon (C), nitrogen (N), phosphorus (P), water) from the food system, and stimulate the reuse and recycling of inevitable resource losses in a way that adds the highest possible value to the food system[104].

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[99] Bal, L., Satya, S., Naik, S. 2010. Solar dryer with thermal energy storage systems for drying agricultural food products: A review. Renewable and sustainable energy reviews. 14(8): 2298-2314.

[100] The Economist. 2019. The Cooling Imperative Forecasting the size and source of future cooling demand. A Report of The Economist Intelligence Unit. www.eiu.com/graphics/marketing/pdf/TheCoolingimpewitative2019.pdf.

[101] Babbitt, C., Neff, R., Roe, B., Siddiqui, S., Chavis, C., Trabold, T. 2022. Transforming wasted food will require systemic and sustainable infrastructure innovations. Current Opinion in Environmental Sustainability. 54: 101151. https://doi.org/10.1016/j.cosust.2022.101151..

[102] Schneider, P., Rochell, V., Plat, K., Jaroski, A. 2021. Circular approaches in small-scale food production. Circular Economy and Sustainability. 1:1231-1255. https://doi.org/10.1007/s43615-021-00129-7

[103] ASABE (Resource). 2021. Transforming food and agriculture to circular systems. Special Issue. 28: 2. March/April. www.asabe.org/Resources.

[104] De Boer, I.J.M. and M.K. van Ittersum, 2018. Circularity in agricultural production. Mansholt lecture, 19 September 2018, Brussels, Wageningen University & Research, 35 pp. www.wacasa.wur.nl

In thinking circular food systems through, De Boer and Van Ittersum (2018) defined four principles for them. These are summarised below.

- Plant biomass is the basic building block of food and should be used by humans first.
- Food and resource losses and waste should be avoided.
- By-products from food production, processing and consumption should be recycled back into the food system.
- Animals should be used for what they are good at (for grassland that cannot be used for other food production).

Fundamentally, the concept of circular food systems has been applied and described also by such terms as 'industrial ecology' or 'industrial symbiosis', meaning that residues (waste) from an entity (business) would become input sources to another, thereby keeping materials in use. An interesting application of the concept in the FAS would be a 'Food-Industrial Park'.

3.5.2. Recirculating aquaculture systems

Fish, including finfish and shellfish, contribute about 17% of global animal-based protein for human consumption and particularly so in developing countries which consume more than 75% while producing over 80% of the global fish supply[105]. A major concern is that the annual number of fish caught in the wild, particularly in oceans, has been stagnating since the 1990's. As the consumption of fish has been growing in the world, aquaculture (fish farming) has developed and almost half of the fish consumed derives from it. Aquaculture production needs are estimated to double from approximately 67 million tonnes (MT) in 2012 to about 140 MT in 2050[106].

Aquaculture, as described above, is primarily based on confined operations in a water environment, whether marine, e.g. 'cages' in the oceans (along coasts predominately), or freshwater indoor and outdoor ponds on land, *Fig. 1.15.*. Over the past several decades, the concept of a recirculating indoor aquaculture system (RAS) has emerged as an alternative system offering the advantages of greatly reducing land use and water requirements compared to ponds. Simply put, water is filtered from the growing tanks (confined environment) and recycled for reuse in tanks. The RAS has been performing well relative to measures of productivity and environmental parameters. A comprehensive treatment of recirculating aquaculture systems is provided by Timmons et al. (2018). Challenges persist because of high capital costs, feed sources, concern about fish diseases, food safety, and consumer acceptance. Consumers are concerned that farmed fish tend to have lower levels of omega-& fatt acids than wild fish (World Resources, 2019). The highly intensive growing environment has also limited acceptance.

Aquaponics can be an added element to a RAS as it combines plants and fish. In an aquaponics system, fish provide waste that effectively fertilises plants, thereby approaching a closed loop system contributing to the circular economy[107]. Plants act essentially as filters, taking out nitrates in the system. The benefits are that little waste is produced from the overall system and inputs are minimised.

Clearly the expected increasing consumer interest in seafoods requires to foster aquaculture generally and RAS specifically. Thus, efforts to intensify aquaculture production by RAS need to be directed at approaches that mitigate the negative issues of RAS.

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[105] OECD-FAO. 2017. Meat-Agricultural Outlook 2018-2027. Chapter 6. www.fao.org/3/i9166e/i9166e_chapter6_meat.pdf.

[106] World Resources Institute. 2019. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2025. Final report. July 2019; Chapter 23 https://research.wri.org/sites/default/files/2019-07WRR Food Full Report_O.pdf

[107] Timmons, M., Guerdat, T., Vinci, B. 2018. Recirculating Aquaculture, 4th edition. Ithaca Publishing Company, LLC. ISBN 978-0971264670

Fig. 1.15. Indoor recirculating aquaculture system
Source: Norman R. Scott (member of the group of authors for this chapter), Intec Open, Evolution of The Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems, Page 15.
https://www.intechopen.com/chapters/78111

3.5.3. Integrating Food, Energy and Water Systems (FEWS)

Water is required to produce food, energy is needed to provide water sources, and this interdependence has been termed the Food, Energy, Water Systems Nexus (FEWS). The agricultural sector (irrigation, livestock and aquaculture) is by far the biggest user of water in the world accounting for 70% of the global total withdrawal. 19% of the world's cultivated land is irrigated, accounting for 300 million hectares, which accounts for almost half of the value of global crop production. In Africa and Asia, 85-90% of all the freshwater is used for agriculture[108]. To satisfy global demand for food, agriculture is expected to increase its water requirements by 2025 by 1.2 times.

Irrigated agriculture plays a major role in the livelihoods of nations all over the world. Although it is one of the oldest known agricultural techniques, improvements are still being made in irrigation methods and practices. During the last four decades, irrigation systems in the world have seen major improvements in technology development. Irrigation has increased by 81 percent from about 153 Mha in 1966; however, the expansion of irrigation might not be as extensive in the next 40 years owing to pressure on water resources due to climate change. Thus, innovative water saving practices are important in the face of predicted water shortages.

Also important is the need to address the water footprint within the agriculture sector. The water footprint of animal products is larger than that of crop products with equivalent nutritional value (*Table 1.1.*). The average water footprint per calorie for beef is about 20 times larger than for cereals and starchy roots. The water footprint per gram of protein for milk, eggs and chicken meat is 1.5 times larger than for pulses[109]. The unfavourable feed conversion efficiency for animal products is largely responsible for the relatively large water footprint of animal products. Their study shows that from a freshwater perspective, animal products from grazing systems have a smaller water footprint than products from industrial animal systems; it is yet more water-efficient to obtain calories, protein, and fat through crop products than animal ones. In addition, water savings need to be addressed at every stage of the food chain from production through consumption.

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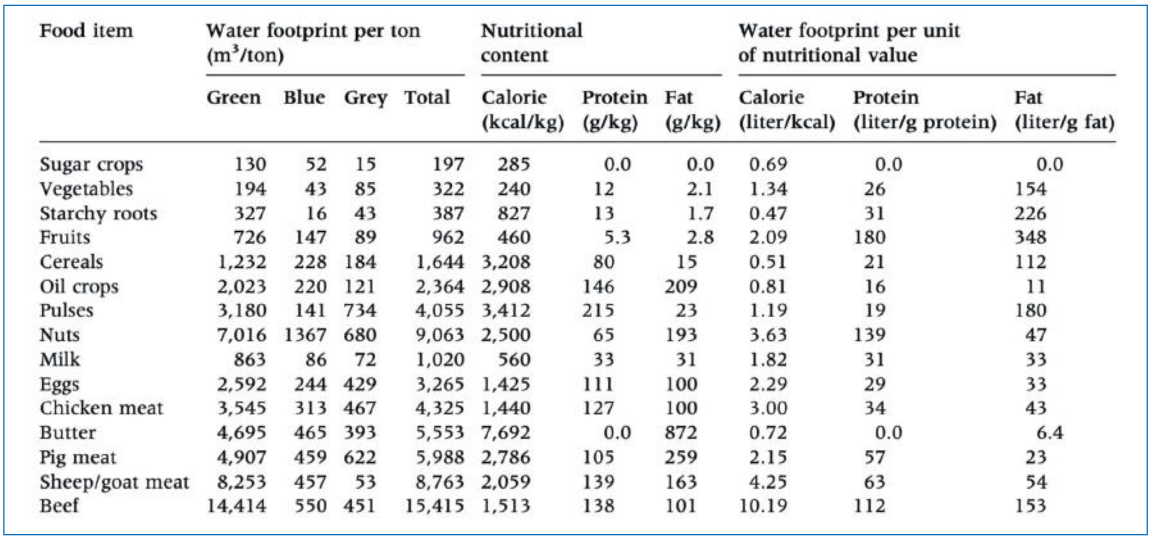
[108] Foley, J., Ramankutty, N., Balzer, C., Bennett, E., Brauman, K., Carpenter, S., Cassidy, E., Gerber,J., Hill, J., Johnston, M., Monfreda, C., Mueller, N. O'Connell, C., Polasky, S., Ray, D., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., West, P. and D. P. M. Zaks. 2011. Solutions for a cultivated planet. Nature 478(7369): 337-342..

[109] Mekonnen, M. and Hoekstra, A. 2012. A Global Assessment of the Water Footprint of Farm Animal Products. Ecosystems 15: 401–415 DOI: 10.1007/s10021-011-9517-8



Food item	Water footprint per ton (m³/ton)				Nutritional content			Water footprint per unit of nutritional value		
	Green	Blue	Grey	Total	Calorie (kcal/kg)	Protein (g/kg)	Fat (g/kg)	Calorie (liter/kcal)	Protein (liter/g protein)	Fat (liter/g fat)
Sugar crops	130	52	15	197	285	0.0	0.0	0.69	0.0	0.0
Vegetables	194	43	85	322	240	12	2.1	1.34	26	154
Starchy roots	327	16	43	387	827	13	1.7	0.47	31	226
Fruits	726	147	89	962	460	5.3	2.8	2.09	180	348
Cereals	1,232	228	184	1,644	3,208	80	15	0.51	21	112
Oil crops	2,023	220	121	2,364	2,908	146	209	0.81	16	11
Pulses	3,180	141	734	4,055	3,412	215	23	1.19	19	180
Nuts	7,016	1367	680	9,063	2,500	65	193	3.63	139	47
Milk	863	86	72	1,020	560	33	31	1.82	31	33
Eggs	2,592	244	429	3,265	1,425	111	100	2.29	29	33
Chicken meat	3,545	313	467	4,325	1,440	127	100	3.00	34	43
Butter	4,695	465	393	5,553	7,692	0.0	872	0.72	0.0	6.4
Pig meat	4,907	459	622	5,988	2,786	105	259	2.15	57	23
Sheep/goat meat	8,253	457	53	8,763	2,059	139	163	4.25	63	54
Beef	14,414	550	451	15,415	1,513	138	101	10.19	112	153

Table 1.1. The water Footprint of some selected food products from vegetable and animal origin (Mekonnen and Hoekstra, 2012).
Source: Mekonnen and Hoekstra, A Global Assessment of the Water Footprint of Farm Animal Products, Ecosystems (2012), page 409.
https://www.waterfootprint.org/media/downloads/Mekonnen-Hoekstra-2012-WaterFootprintFarmAnimalProducts.pdf

3.5.4. Improving energy consumption through technology

The use of energy in agriculture has allowed farms to create food; yet such energy use tremendously varies across the agriculture and food system. *World Energy Balances*[110] provides comprehensive data on energy balances for all the world's largest energy producing and consuming countries. It contains detailed data on energy supply and consumption for over 155 countries, economies, and territories, including all OECD countries, and more than 100 other key energy producing and consuming countries, as well as 35 various regional aggregates and world totals. As a first priority, the focus across the food value chain needs to be on energy conservation and efficiency to reduce its consumption as it directly and indirectly drives decarbonisation.

As the rest of the global economy, the agri-food sector is gradually reducing its dependence on fossil energy, the total renewable energy contribution being about 6% (a nuclear energy contribution of 8% is excluded from the renewable pool). Current commercial biofuels conversion processes are classified as 1st, 2nd, and 3rd generation technologies because of a strong reliance on food crops as seen in *Table 1.2.*. Traditionally, bioethanol is produced from edible carbohydrates via a number of pre-treatment steps prior to enzymatic fermentation and product purification steps. This is the case with corn-to-ethanol and sugarcane-to-ethanol, and a typical ethanol biorefinery is in *Fig. 1.8.*. It should be noted that a significant byproduct from the biorefinery is dry distillers' grains which is a valuable livestock feed.

Biorefinery technology	Type of biomass feedstock
1st generation	Edible crops (sunflower, sugarcane, corn, soybeans, palm, rapeseed, etc.)
2nd generation	Agro-residues (lignocellulosic)
3rd generation	Algae
4th generation	Non-edible plants (jatropha, soapnut, rubber seed, candlenut, etc.), food waste.

Table 1.2. Classification of biorefinery technology according to biomass feedstock

In addition, the agricultural sector has developed strong links with renewable energy sources[111]: biorenewables constitute about 47% while the balance is ascribed to wind, geothermal, hydro, and solar facilities.

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[110] IEA (2021), World Energy Balances: Overview, IEA, Paris https://www.iea.org/reports/world-energy-balances-overview

[111] IRENA and FAO. 2021. Renewable energy for agri-food systems - Towards the sustainable development goals and the Paris agreement. Abu Dhabi and Rome. https://doi.org/10.4060/cb7433en

Hydroelectricity features prominently in the renewable energy supply to FAS either through the National grids or off-grid situations (in rural locations where small dams on rivers provide both power and water for irrigation).

The use of locally available renewable energy sources, together with energy-efficient technologies, has become increasingly attractive to minimise impacts of rising energy costs on agri-food profitability, competitiveness, and climate effects. The contribution of different types of renewable energy sources to the overall renewable consumption by the FAS depends on the national policies for renewable energy. In the United States of America for example, there has been a steady increase in the number of agricultural operations with on-farm renewable energy producing systems (wind turbines, small hydropower, solar panels, methane digesters, biodiesel, bioethanol, etc.) over the past decade (2012-present) with solar panels as a leading source. Results of a 2021 survey report that 37% of British farmers are using renewable energy and that 35% plan to invest in renewable energy generation[112].

3.5.4.1. Bioenergy

Bioenergy mobilisation varies greatly by country, both in terms of relative importance and by source of energy, and may be a key in some countries. At the global level, forestry products such as wood fuel (solid biofuel), charcoal, wood chips and pellets contribute about 85% of all the biomass utilised for energy purposes while agriculture accounts for about 10% of the global biomass supply (World Bioenergy Report, 2020)[113]. Consequently, agriculture is a key sector for increasing biomass contribution and the potential for bioenergy utilisation. The principal agricultural feedstocks include crop residues such as rice husks and wheat straw as well as biofuel crops exemplified by palm oil, sugarcane, oilseeds, etc. The role of bioenergy in the FAS is especially prominent in Africa and the developing world where a small-scale operation is the predominant mode of agricultural practice and food production. For example, gari, a common staple in the West Africa subregion, is produced from cassava fermentation[114] from which the resulting wet solid obtained after slurry filtration is dried and slowly roasted to taste in large open metal bowls over wood fuel-fed clay furnaces.

For cooking and other food preparation processes, biomass burning is the principal source of energy provision in developing countries. Pakistan, for example, utilises 86% of the nation's total biomass energy in the household sector[115] while the estimate for Nigeria is 96%[116]. In fact, about 80% of Nigerians in rural and urban areas depend on biomass combustion for food processing needs. Although this estimate is not representative of the entire continent, the associated detrimental effect is significant at the regional level because Nigeria's population (about 215 million) is about 20% of a continent that includes the Sahara Desert (9.2 million square kilometres). In practice, wood fuel burning results in considerable deforestation which exacerbates global GHG emissions, directly and indirectly through changing land use. Conceivably, periodic droughts particularly in Somaliland (located in the Horn of Africa), may be attributed to the local practice of felling trees for wood fuel, which not only aggravates the food-energy demand for cultivated land but also has deleterious effects on climate change through reduction in CO_2 sequestration and the release of CO_2 due to combustion. In advanced economies, however, biomass (commercial crop residues, energy crops, wood waste, black liquor, municipal solid waste, etc.) is often converted to liquid and gaseous fuels (biofuels – biodiesel and bioethanol- and biogas respectively) for transportation fuels, in heating systems, and in electricity generation. In Australia, about 1.4% of the total electricity production (3 164 GWh) is attributed to bioenergy in 2020[117].

Although natural gas (essentially methane) is presently cheaper than biogas, the latter could be a renewable replacement if properly treated and may therefore be an addition to the portfolio of low-carbon technologies in the FAS. The ambitions of the EU to greatly reduce its reliance on Russian fossil fuels encourages interest and

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[112] NFU (National Farmers' Union). 2021. Farmers prioritising sustainability investments, NFU survey shows. https://www.nfuonline.com/media-centre/releases/farmers-prioritising-sustainability

[113] World Bioenergy Association Report. 2020, Chapter 6. https://www.worldbioenergy.org/uploads/210331%20WBA%20Annual%20Report%202020%20Public%20Version.pdf

[114] Ofuya CO, Adesina AA, & Ukpong E., 1990. Characterization of the solid-state fermentation of cassava, World J. Microbiol. & Biotech., 6, 422-424. doi: 10.1007/BF01202126.

[115] Saeed MA, Irshad A, Sattar H, Andrews GE, Phylaktou HN & Gibbs BM, "Agricultural Waste Biomass Energy Potential in Pakistan", In: International Bioenergy (Shanghai) Exhibition and Asian Bioenergy Conference, 21-23 October 2015, Shanghai, People's Republic of China.

[116] Olanrewaju, F.O., Andrews, G.E., Li, H., Phylaktou, H.N., 2019. Bioenergy potential in Nigeria, Chem. Eng. Transactions, 74, 61-66.

[117] Clean Energy Council. 2020. Bioenergy.

expansion for biomethane. The production of renewable natural gas (RNG) from biogas upgrade using different technologies (e.g., amine scrubbing, membrane separation, pressure-swing adsorption, and water-wash) is one such approach on large agricultural farms (dairy and swine farms) in the USA. RNG is readily used for heating, cooking and as vehicle fuel[118]. The techno-economic assessment of RNG is favourable under the existing California environmental policy framework. Technologies for the conversion of RNG to high value-added green fuels such as biomethanol and biohydrogen are also improving the energy economics of the agri-food chain[119].

Globally, biogas development is still relatively limited for various reasons including inadequate information about biogas possibilities, the cheaper cost of natural gas (fossil resource), high capital costs of current commercial biogas plants, and lack of national and local government policies to support biogas programs, as well as policies which are barriers to adoption. As a result, there is very little global data on the current installed capacity of biogas plants except for Germany and the USA. India and China are acknowledged leaders in biogas production with estimates of 4.5 million m^3 and 40 million m^3 plants respectively for heating water, cooking, and lighting. The World Bioenergy Association estimated an annual global biogas production of 30-40 billion m^3 (equivalent to 1080-1440 PJ e.g., 300-400 TWh). It is therefore apparent that biogas from the FAS if fully utilised, could supply about 6% of current global primary energy needs, even if, when burning, biogas produces CO_2.

An intriguing utilisation of biomass (animal manure, other forms of organic waste such as slaughterhouse waste, crop biomass and crop residues) is the generation of bioenergy that has led to the creation of bioenergy villages in Germany[120]. In Germany alone, there are more than 50 bioenergy villages with numerous additional ones at the planning or implementation stage. An anaerobic digester is designed to convert local biomass (organic materials) to biogas to operate a combined heat and power (CHP) unit (usually an internal combustion engine connected to an electric generator) to provide heat and electricity. Heat is provided to village homes by an underground pipe loop thereby forming a district heating approach. Where waste heat from the CHP unit is inadequate to meet the heating needs of the village (largely during winters), woody biomass is burned in a furnace to provide the necessary hot fluid (water) to supplement heat available from the CHP unit. Although highly site specific, the concept of the bioenergy village can potentially offer an opportunity for the "decarbonisation" of rural areas and support sustainability.

3.5.4.2. Biofuels

Biofuels consisting mainly of biodiesel and bioethanol (although other bio-alcohols in the C_1 to C_4 class are also produced in relatively small quantities) are produced from plants, animal waste and algae via various transformation processes. In view of its biological origin, the global production of biofuels may be attributed to FAS (95% of global bioethanol is from agricultural products). *Fig. 1.16.* shows the production trend within the past two decades.

The top 5 leading producers of liquid biofuels are the USA, Brazil, Indonesia, Germany, and China. Additionally, both the USA (52,6 billion litres) and Brazil (30,01 billion litres) produced about 84% of the global bioethanol output in 2020 as shown in *Fig. 1.17.*. Corn is the principal feedstock used for bioethanol production in the USA, sugarcane is the key input in Brazil. Typical commercial plants employ 1st, 2nd and 3rd generation technologies (see definitions in *Table 1.2.*). The food vs. energy crop debate has however encouraged the development of 2nd generation technologies and beyond generation technologies that rely on non-edible biomass resources. In general, bioethanol is used as a transportation fuel (blended with gasoline as E10 and E85 variants in the USA), for powering fuel cells and in the manufacture of biodiesel. Thus, both bioethanol and biodiesel are utilised for vehicular operation (tractors, harvesters, freight trucks, etc.) in the FAS and in other sectors.

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[118] Chemical Engineering Progress. 2021. Special section: Renewable natural gas. September 2021 issue. www.aiche.org/cep

[119] Biofuels Digest. 2022. WasteFuel launches to turn agriculture waste into green fuel. Biofuels Digest https://www.biofuelsdigest.com/bdigest/2022/02/13/wastefuel-agriculture-launches-to-turn-agriculture-waste-into-green-fuel/

[120] Jenssen, T,. König,A., and Eltrop, E. (2014) Bioenergy villages in Germany: Bringing a low carbon energy supply for rural areas into practice. Renewable Energy 61:74-80.

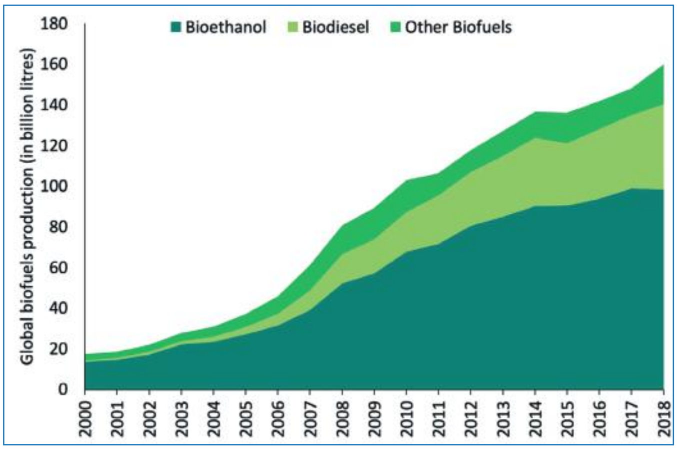
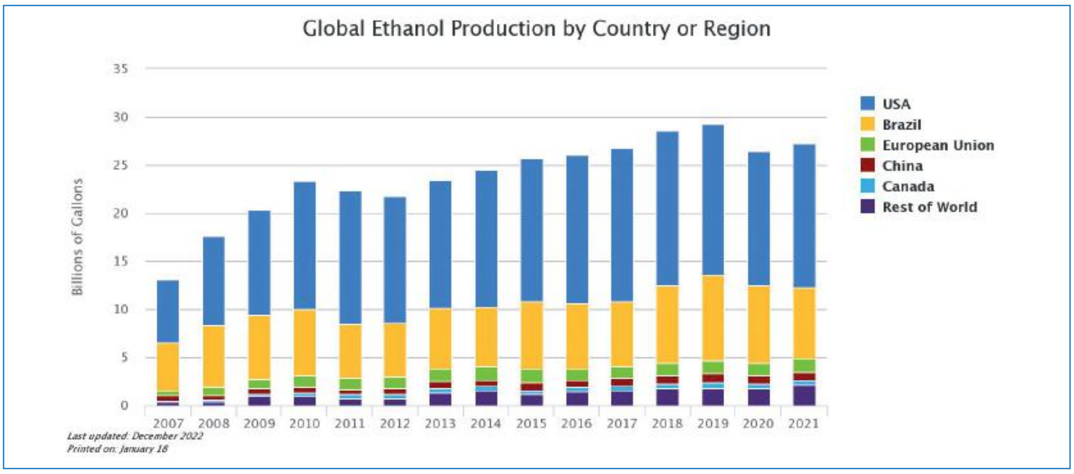


Fig. 1.16. Global production history for liquid biofuels (Chemical Engineering Progress, 2021)[118]
Source: Global Bioenergy Statistics 2020 produced by World Bioenergy Association, Chapter 6, p49, Figure 58. Reproduced with permission
Reference: https://www.iea.org/data-and-statistics
(https://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf)



Last updated: December 2022
Printed on: January 18

Fig. 1.17. Trends in bioethanol production for selected countries/regions
Source: "Global Ethanol Production by Country or Region" 2023. U.S. Department of Energy, Alternative Fuels Data Center. Accessed January 15, 2023. afdc.energy.gov/data/10331
https://afdc.energy.gov/data/10331

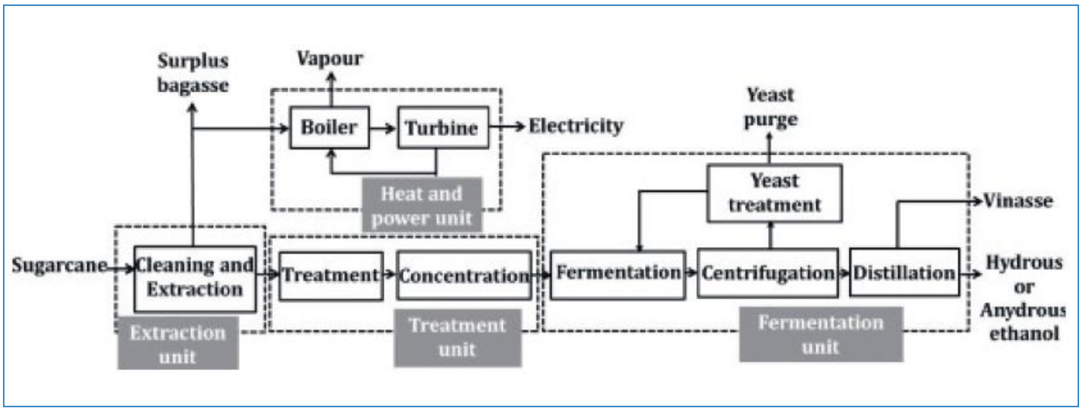


Fig. 1.18. Block diagram of a Brazilian ethanol production facility
Source: Assessing the Performance of Industrial Ethanol Fermentation Unit Using Neural Networks. CCC RightsLink License N° 5471400721280
https://www.sciencedirect.com/science/article/pii/B9780444642356500322

In recognition of the energy-food security debate and the many controversies about the relevance and opportunity to produce and promote biofuel when considering the competition with food production, recent technological developments related to the production of bioenergy from non-food sources include conversion processes for cellulosic and algae-biomass as well as non-edible and spent vegetable oils. These transformation routes include low- (enzymatic) and high-gasification, pyrolysis, hydrothermal liquefaction, temperature deconstruction. These new processes are part of a portfolio of advanced bioenergy technologies promoting investment in the food-energy-water nexus for new frontiers in sustainable development.

Advanced bioethanol processes employ various techniques including the utilisation of novel biomass sources through to integrated biorefineries that produce additional high value-added products (oxygenates, organic acids, etc.) as alternatives to conventional petrochemical derivatives, thereby helping reduce greenhouse gas emissions. Specifically, novel biomass sources include (i) novel biomass sources such as the organic fraction of municipal solid waste and some industrial residues from the paper, food, and beverage production facilities; (ii) the incorporation of new pre-treatment methods for the fractionation and conversion of lignocellulosic materials e.g., bio-extrusion and novel ionic liquids; and (iii) the utilisation of new enzyme systems and microbial strains during saccharification and fermentation processes. Furthermore, employment of non-edible biomass might also reduce land competition between food and energy production and the propensity for deforestation.

In one approach, the fermentation of potato waste (spoiled potatoes and low-grade potatoes) is used to obtain bioethanol, acetone, butanol, lactic acid, and other oxygenated intermediates in order to produce biodegradable and biocompatible PLA polymers that are environmentally friendly instead of petro-based polymers. Defining the scientific and engineering aspects in terms of yeast selection, fermentation kinetics, bioreactor design (batch, fed batch and continuous operation) has been a subject for research in the past two decades[121, 122]. An improvement in the production of biodiesel beyond the 1st generation route (direct esterification reaction between alcohol and high molecular weight fatty acids, e.g. palmitic, oleic, linoleic, etc.) has been achieved via transesterification of non-edible oils and microalgae leading to 2nd and 3rd generation biodiesel production route[123] as schematically depicted in *Fig. 1.19.*.

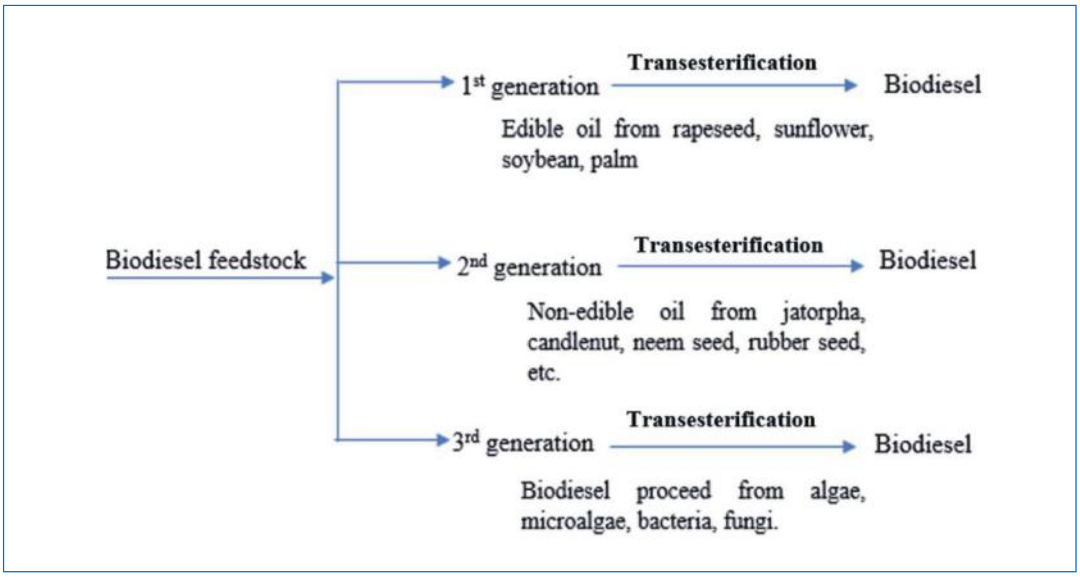


Fig. 1.19. Biodiesel production technology pathways
Source: Shaah et.al., 2021, A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies, Page 4, Royal Society of Chemistry CC BY-NC
https://pubs.rsc.org/en/content/articlehtml/2021/ra/d1ra04311k

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[121] Kaur, L., Singh, J., 2009. Novel Applications and Non-Food Uses of Potato: Future perspectives in nanotechnology, Special issue of Advances in Potato Chemistry & Technology, Chapter 15, 425-445. https://www.sciencedirect.com/science/article/pii/B9780123743497000155;

[122] Karapatsia, A., Penloglou G., Chatzidoukas, C., Kiparissides, C., 2015. Development of a Macroscopic Model for the Production of Bioethanol with High Yield and Productivity via the Fermentation of *Phalaris aquatica* L. Hydrolysate. Comput. Aided Chem. Eng., 37, 2129-2134, 2015.

[123] Shaah MAH, Hossain MS, Allafi FAS, Alsaedi A, Ismail N, Kadir MOA & Ahmad MI. 2021. A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies, RSC Advances, 11, 25018.

Transesterification involves the tripartite reaction between alcohol, carboxylic acids and the triglycerides present in these oils to enhance biodiesel yield. Processing challenges arising from the co-product, glycerol, have been addressed by the application of an innovative process intensification design to produce biodiesel yield and purity higher than the thermodynamic limitation[124]. The integration of ethanol fermentation with biodiesel refinery is another advanced process development initiative to reduce overall energy consumption. It decreases separation costs, improves microbial cell recovery and reuse (with attendant fermentation at high cell densities and superior ethanol volumetric productivity, etc.).

Moreover, recent developments in the generation of electricity from agri-waste-fed microbial fuel cells (MFCs)[125] further strengthen confidence in this projection given that MFCs are especially adaptable for small-scale farming operations via mini-grid technologies. Thus, the current disparity in the shares of energy consumption along the agri-food chain between high and low GDP countries may be reduced. It is also evident that in addition to power generation, MFC simultaneously delivers pollutant-free, hygienic water which may be recycled for farm use. However, some significant challenges do exist in terms of high operating costs, low power output, electrode performance, possible bio-toxicity of some heavy metals, and issues of scaling up.

3.5.4.3. Biochar

Biochar which is obtained from the carbonisation (pyrolysis and hydrothermal treatment) of biomass (processed or unprocessed) is important for the realisation of long-term carbon sequestration along with other beneficial effects on soil fertility, water management and environmental attributes. Modern studies have shown that ancient civilisations in South America may have intentionally used *terra preta* (black earth) - a type of biochar obtained from forest burning - to enhance soil fertility for crop production[126]. As may be seen in *Fig. 1.20.*, the energy produced during the process may be recycled to improve the overall efficiency of the agri-food chain. The biochar role in the FAS will experience increasing utilisation, especially in the developing world where rapid urbanisation and increased wealth with attendant growth in the agro-processing industry will lead to higher levels of organic waste, which will need to be managed in a sustainable manner. India, China, Egypt, Vietnam, Ethiopia and Cameroon have biochar production projects aimed at improving agricultural lands and climate change mitigation as illustrated in *Fig. 1.21.*.

The USA biochar market (about 65% of the global capacity) is estimated at over USD 125 million in 2020 and is expected to increase nearly 17% (compound annual growth rate) over the next decade. Annual biochar output from the USA is about 50 000 tonnes[127]. The market shares for Europe, Asia and Africa are 25%, 7% and 3% respectively with consumption almost exclusively in the FAS of each region. Nevertheless, the economics of biochar production is still debatable given that pyrolysis is an energy-demanding operation. A life cycle assessment of biochar systems[128] analysed several biomass systems (corn stover, switchgrass, and yard waste) for net GHG emissions and economic viability and states that benefits depend on feedstock selection.

Biochar could provide moderate to large mitigation potential[129]. Medium evidence suggests that biochar has a technical potential of 2.6 (0.2-6.60) $GtCO_{2e}$/year. However, mitigation and agronomic benefits depend strongly on the type of biochar and the properties of the soil to which it is applied.

The review of 112 scientific papers[130] on studies of biochar as a feed supplement to improve animal health, increase nutrient intake efficiency and thus productivity have shown mixed results. Several have pointed to a reduction in methane emissions from ruminants, others no significant change. This is therefore calling for further research.

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[130] Schmidt H-P, Hagemann N, Draper K, Kammann C. 2019. The use of biochar in animal feeding. PeerJ 7:e7373 DOI 10.7717/peerj.7373

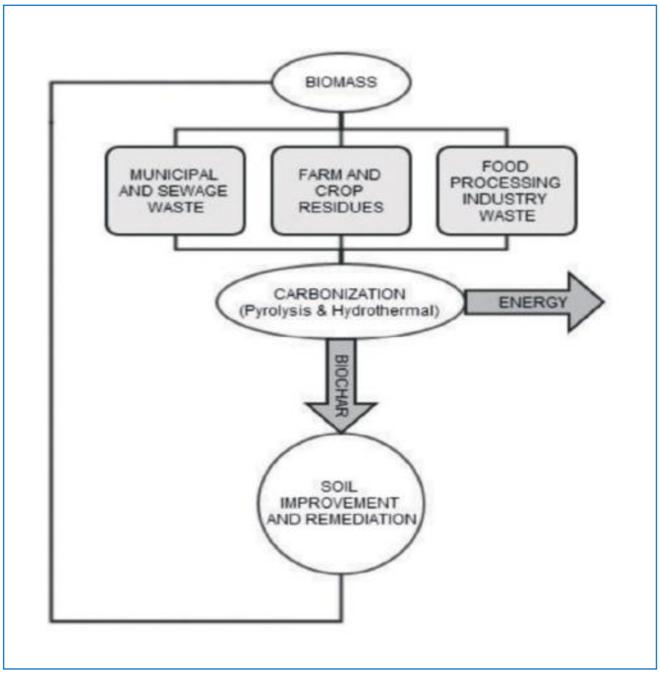

Fig. 1.20. Biochar production from the valorisation of organic waste.

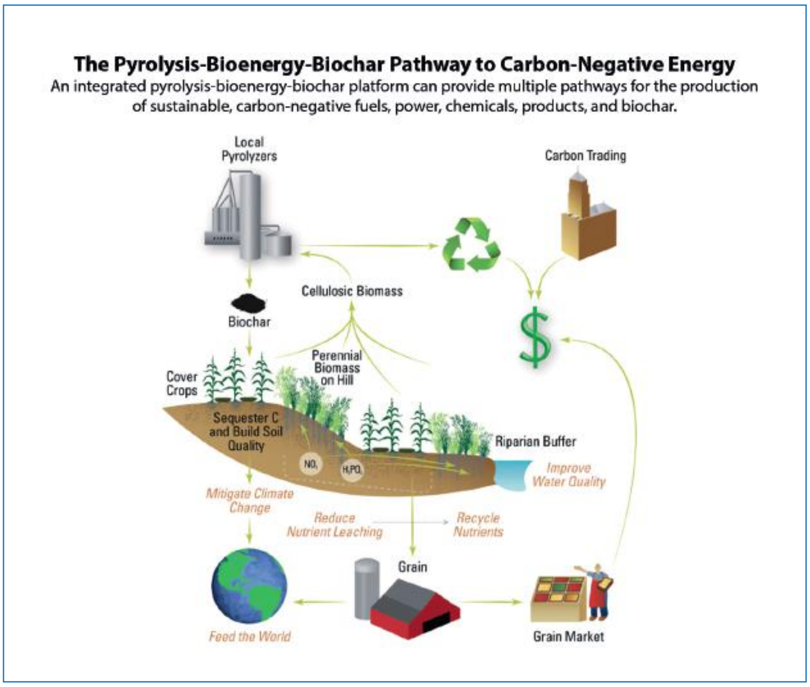

Fig. 1.21. Synergy between agriculture, energy and environment via the biochar loop (Farm Energy, 2019)[131]
Source: David Laird, Iowa State University, reproduced with permission
https://www.biorenew.iastate.edu/research/thermochemical/biochar/pathway.

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[131] https://www.academia.edu/25743192/Woody_Feedstocks_Management_and_Regional_Differences_In_Braun_R_D_Karlen_and_D_Johnson_ed_Sustainable_Feedstocks_for_Advanced_Biofuels_Sustainable_Alternative_Fuel_Feedstock_Opportunities_Challenges_and_Roadmaps_for_Six_U_S_Regions

3.5.4.4. Solar energy and the co-location opportunity

The challenges of meeting the needs of food, energy, and water (frequently called a nexus) in the face of climate change have stimulated some innovative novel systems to co-locate agriculture and solar photovoltaics (PV), termed ‘agrivoltaics’ (*Fig. 1.22.*). The concept originally suggested by Goetzberger and Zastrow (1982)[132] has been further developed and analyzed by Adeh et al. (2019)[133], Baron-Gifford et al. (2019)[134], Dinesh et al. (2018)[135], Dupraz et al. (2011)[136]. At present, solar PV is being employed by large utility-grid systems and on rooftops but the opportunity to develop an integrated system coupling the application of PV and crop production on the same land maximises land use without sacrificing crop land. In fact, a study of co-location in drylands has shown synergistic benefits. The shading created by the PV panels reduces heat stress on plants, which will improve yield, while transpiration from plants reduces the temperature of panels improving energy production. The development of enhanced semi-transparent PV panels would further support the co-location of PV panels and crop land.

In this perspective, one approach is to elevate solar PV panels (‘on stilts’) to allow animals and equipment to move beneath the panels; another option could be ground mounted PV panels separated by an area between panels for farming[135]. At this point, the number of crops which have been evaluated under PV panels is limited. Moreover, the impact of PV panels on the microclimate of air temperature, wind speed and relative humidity needs significant study to assess plant response. Some studies have shown benefits for crops like tomatoes, and lettuce[133]. Solar farms that have been monitored regularly by ecologists in the UK have demonstrated an increase over time in the abundance and variety of plants, pollinators, birds, and other wildlife[137].

Another unique example would be co-location of solar PV panels installed over irrigation canals and reservoirs; this was suggested as an experiment in California to obtain the benefit of electricity while simultaneously reducing the evaporation from the typically uncovered water surface[138]. Other examples exist with installations in India and proposed applications in France.

Fig. 1.22. Illustration of co-location of solar PV panels and agricultural land with cropping. Reproduced with permission
Source: Kirk Siegler/NPR, November 14, 2021: “This Colorado ‘solar garden’ is literally a farm under solar panels”
https://www.npr.org/2021/11/14/1054942590/solar-energy-colorado-garden-farm-land

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[132] Goetzberger, A., Zastrow, A., 1982. On the coexistence of solar-eneroy conversion and plant cultivation. Int. J. of Solar Energy. 1(1):55-69. https://doi.org/10.1080/01425918208909875

[133] Adeh, E., Good, S., Calaf, M., Higgins, C. 2019. Solar PV power potential is greatest over croplands. 2019.natureresearch, scientific reports. 9:1142. https://doi.org/10.1038/s41598-019-47803-3

[134] Baron-Gafford, G., Pavao-Zuckerman, M., Minor, R., Sutter, L., Barnett-Moreno, I., Blackett, R., Thompson, M., Dimond, K., Gerlak, A., Nabhan, G., Macknick, E. 2019. Nature sustainability. 2(848-855)

[135] Dinesh, H., Pearce, J., The potential of agrivoltaic systems. 2018. Renewable and Energy Reviews. 54(299-308). https://dx.doi.org/10.1016/j.rser.2015.10.024

[136] Dupraz, C., Marrou, H., Dufour, L.,Nogier, A., Ferard. Y. 2011. Combining solar photovoltaic panels and food crops for optimizing land use: Toward new agrivoltaic schemes. Renewable Energy. 36(2725-2732). doi: 10.1016/j.renene.2011.03.005.

[137] Solar Energy UK. 2022. Everything under the sun : The facts about solar energy. Solar Trade Association UK. Chapter House, 22 Chapter St, London, SW1P 4NP. https://solarenergyuk.org/wp-content/uploads

[138] McKuin, B., Zumkehr, A., Ta, J., Bales, B., Viers, J., Pathak, T., Campbell, J. 2021. Energy and water co-benefits from covering canals with solar panels. Nat Sustain 4, 609–617 (2021). https://doi.org/10.1038/s41893-021-00693-8

3.5.4.5. Wind energy and the co-location opportunity

Much has changed since the early 1900's when many farmers used wind power to pump water and generate power from relatively small windmills. Today, large wind turbines with generating capacity well above 1MW are common on agricultural land, particularly in the USA and Europe, (*Fig. 1.23.*). Like solar PV, co-location of wind turbines on agricultural land has become common. Farmers can lease land to wind developers[139], own turbines to generate power for their farm, form a group of farmers or become wind developers . Many farmers have found wind turbines on their land to be an important source of income. Typically, large turbines use a half-acre or less of land, including the access road, while allowing farming operations for cropping and grazing of livestock up to the base of turbines. As one farmer has been known to say, "it is a lot easier to milk a wind turbine than cows". Another example of wind energy being used in the FAS is an installation of wind turbines and solar PV panels at a brewery in California. Increasingly, industries along the food value chain are implementing solar and wind sources to electrify their activities.

Fig. 1.23. Integration of large winds turbines co-located on agricultural land.
Photo by Norman R. Scott, member of the group of authors for this chapter.

3.5.4.6. Geothermal systems

Geothermal energy can be an attractive option if low-cost, low-enthalpy geothermal sources are available. These include geothermal resources at shallow depth, water co-produced from onshore and offshore hydrocarbon wells or already existing deep wells, and residual heat from geothermal power plants. Geothermal energy is accessible day and night every day of the year and can thus serve as a base (constant) energy source against intermittent sources. Geothermal energy is an infinite heat energy source because of the long life of radioactive isotopes (K-40, U-238, Th-232). However, the capacity of production may be restrained by limited available water. In practice, only the ground source and 'conventional' fluid-stream geothermal energy are currently used. To increase the amount of geothermal energy utilised in FAS, we need to use the available sources in multistep cascade systems as shown in *Fig. 1.24.*.

Geothermal energy can be used in aquaculture, irrigation, soil heating, food/crop drying, greenhouse heating, milk pasteurisation, evaporation and distillation, refrigeration, sterilisation. The concept of cascade utilisation is an effective way to sustainably exploit the high potential of geothermal resources classified as medium and low enthalpy. In the future, the deep, dry, high temperature geothermal sources (hot dry rock, or HDR) and enhanced geothermal systems (EGS) should be increasingly utilised in multistep cascade systems in the FAS.

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[139] NREL (National Renewable Energy Laboratory). 2022. A clear vision for wind enhancement. https://www. nrel.gov.

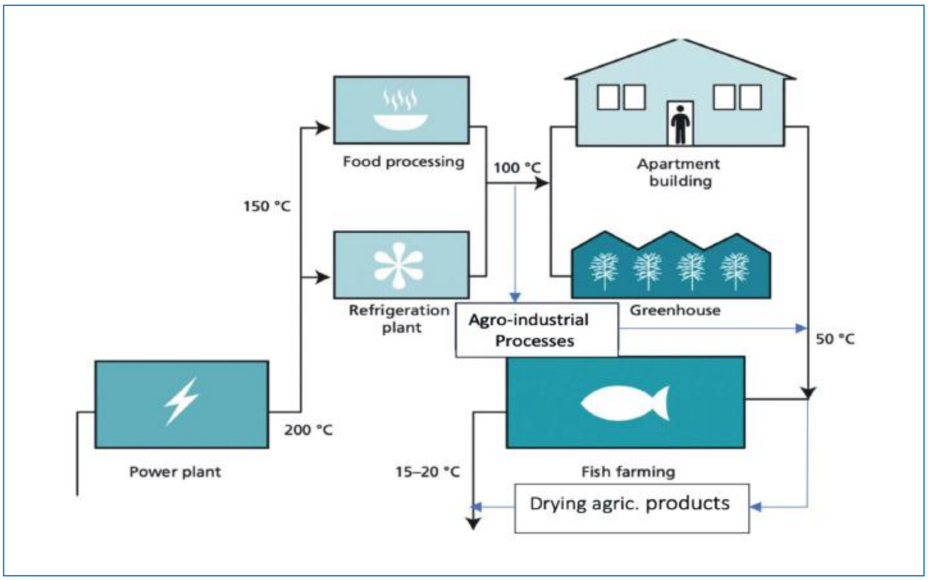

Fig. 1.24. Cascade use of geothermal energy illustrating applications in the FAS (adapted and modified from Lund, 2010,[140] Fig. 11) https://doi.org/10.3390/en3081443

3.5.4.7. Electrification and electricity on the farm

Electric vehicles are revolutionising the sector of transportation. This revolution is also taking place in agriculture, but is still at an early stage with numerous equipment manufacturers launching or working on the development of autonomous electric tractors[141]. Companies that manufacture tractors are investing heavily in electric tractors, which are at various stages in their development with limited availability beginning in 2022. These tractors are equipped with autonomous hardware, replete with many sensors and machine learning for data collection and tractor control. At this point, the development of the electric tractor has been focused in the 30-40 horsepower (or 25-30 kW) range, largely due to the size and weight of batteries. An advantage of smaller equipment is its potential for reduced soil compaction.

First perceptions are this high technology would be only applicable and affordable in 'industrialized' agriculture. Electric-driven tractors and equipment are certainly conceivable in the developing world because smaller tractors and machines are well adapted to the small land holdings. The authors envision the co-development of solar PV for charging batteries to power electric equipment. Rapid advancements in battery technologies and decreasing cost will be keys to adoption in the developing world. A unique idea of a cord-connected electric tractor (equipment) might well be an excellent way to connect solar PV to power electric equipment for the small farmer, in particular in the developing world. This approach has advantages of no battery which reduces cost and soil compaction because of reduced weight; all be it with limited range.

3.6. Advanced non-specific technology for FAS decarbonisation

3.6.1. Computing and information science: Digital Agriculture, or 'Digital Ag'

Digital Agriculture, broadly stated, theoretically offers the possibility of benefits to both large and small producers. Digital agriculture is for instance spreading in Africa through cell phones and two main applications: advice and market prices. Yet, when it comes to embracing computer and information science through the integration of sensors, satellites, tablets, and cell phones, it is still essentially implemented by large farms. Research, teaching, and extension (outreach) programmes in Digital Agriculture have been developed in many universities around the world. Like sustainability, Digital Ag is defined or described somewhat differently by various proponents. One such description of Digital Ag is given in *Fig. 1.25.* and illustrates the linkages of innovation, discovery, and analytics with broad applications to areas throughout the food value chain of the FAS.

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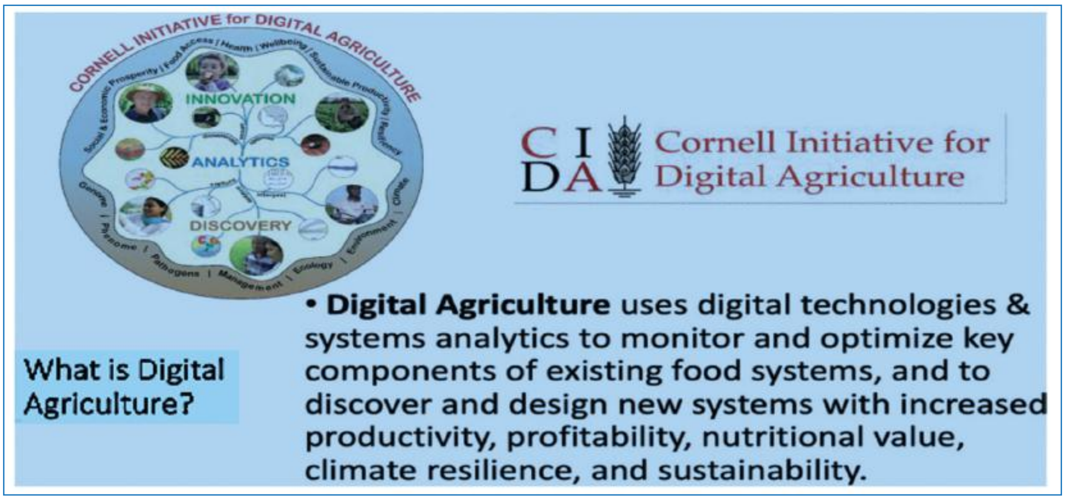
[140] Lund, J.W. 2010. Direct utilization of geothermal energy. Energies 3(: 1443-1471. https://doi.org/10.3390/en3081443

[141] Future Farming. 2022. A website with continuing information frequent updates in racking electric autonomous equipment, including tractors. https.www.futurefarming.com



What is Digital Agriculture?

- **Digital Agriculture** uses digital technologies & systems analytics to monitor and optimize key components of existing food systems, and to discover and design new systems with increased productivity, profitability, nutritional value, climate resilience, and sustainability.

Fig. 1.25. Use of digital technologies in agriculture
Source: Intec Open, Evolution of The Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems, Norman R. Scott, member of the group of authors for this chapter, Page 5

The capability of Digital Ag ultimately depends on the integration and connectivity of critical elements for a successful system, broadly categorised by Scott (2020)[142] as:

- **sensors** (including drones, robotics, artificial intelligence) to initiate data acquisition in the field;
- **connectivity with autonomous transfer of data** from sensors (likely many: an Internet of Things Agriculture, or IoTA) by wireless communication between digital devices, e.g. computers, tablets, and smartphones;
- **analytical devices** with software capability (machine learning, artificial intelligence, and handling of ‘big’ data) for storage, analysis, synthesis and the reporting of results;
- **organisations** (start-ups, consolidations, and market developments) to apply recommendations to practice in the field.

Bellon-Maurel et al. (2022)[143] identified four pillars that are essential for digital agriculture: (i) large data acquisition (sensors, crowd sourcing, etc.); (ii) Artificial intelligence and HPC; (iii) connections, data transfer, networks; and (iv) robotics and automation. They also highlight the importance of the institutional ecosystem (skills, innovation, start-ups, etc.) and of public policies to get the most out of the digital technology and contribute to the transition to sustainable agriculture and food systems.

3.6.2. Sensors

It all begins with sensors and with great advancements in sensor development; it is possible to study plant and animal physiology beyond the laboratory to measure, monitor and launch actions in plant, animal, and microbial production systems. Adding the Internet of Things to agriculture (IoTA), big data analysis, and artificial intelligence promotes a form of high-tech agriculture driven by data. Sensors and biosensors have been a major area of research and development, especially in nanoscale science and technology applications. In the section on nanotechnology, we note an extensive use of sensors in the processing, distribution and storage stages of the food value chain. Many companies in the world are actively producing an array of sensors to foster an increasing shift across the spectrum in digital agriculture, from the stage of research to that of design for use in field applications.

3.6.3. Robotics and automation

Robots have clearly been transferred from many industrial applications to provide a significant new technology in the FAS. Such technology has contributed to many different applications in labour-intensive crops. It has been used for example: (i) to identify weeds and implement weed control (e.g. to mechanically remove weeds, em-

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[142] Scott, N. 2021. Evolution of the soil-based agriculture and food system to biologically- based indoor systems. In : Technology in Agriculture. Eds. Ahmed, F. and Sultan, E. London :In TechOpen. DOI: http://dx.doi.org/10.5772/intechopen.99497

[143] Bellon-Maurel V., Brossard L., Garcia F., Mitton N., Termier A., 2022. Agriculture and Digital Technology: Getting the most out of digital technology to contribute to the transition to sustainable agriculture and food systems. pp.1-198, INRIA-INRAE. https://doi.org/10.17180/wmkb-ty56-en

ploy microwave technology to kill weeds, and other methods); (ii) to spot the onset of plant diseases or pests and deliver intervention schemes (e.g. for citrus greening, early potato blight, and many more); (iii) to deliver fertiliser, pesticides, and herbicides at specific sites; (iv) to spot and control spray delivery in vineyards and orchards (including pollinator applications); (v) for robotic 'ducks' in rice fields to control weeds without pesticides; (vi) with robots to pick fruits (e.g. apples, citrus, strawberries, raspberries and more), (vii) in robots for transplanting; (viii) in soil robots for soil testing and determining water-use effectiveness; (ix) within food processing plants, robots to size, sort and package products; and (x) within autonomous robotic vehicles (including tractors, some of which are electric) to perform field operations that could reduce soil compaction and simultaneously track data.

Robots have entered the dairy farm to milk and feed cows. Cows enter a special stall and are milked while feed is available during milking, based on milk production. Access to the milking stall is based on n times milking per day as a function of the cows' milk production. The identity of each cow is transmitted by an electronic animal tag, and sensors within the teat cup provide data on temperature, milk conductivity, and milk quality. A highly desirable future biosensor would detect progesterone levels that could provide key data on reproductive status (estrus). A single robot station can handle about 50 cows per day, which makes the system compatible with small farms as well as large farms. The milking robot has been adopted on small farms to address such challenges as the unavailability of human labour, freedom from the daily minimum commitment of twice milking, thus permitting a normal life; and, because the cow can be milked more often, increased production has been experienced. Moreover, a few large rotating milking parlours with robotic milking units have been installed across the world.

The development and production of field and harvest robots is a global business. *Future Farming* (2022)[144] produced a robot catalogue identifying more than 35 field and harvest robots from sixteen countries. In this first edition, seven of the robots are manufactured in the USA and six from the Netherlands. It is anticipated that numbers will continue to increase significantly in the future.

Yet the promotion of mechanisation may raise important sustainability concerns. As stated by the Malabo-Montpellier Panel (2018)[145], in the case of Africa, "with new emerging machines and technologies on the horizon, it is ever more important that governments design mechanisation strategies that generate new employment opportunities for those working in the rural on- and off-farm economies. This is particularly important given how critical employment is to reducing poverty and migration and maintaining political stability".

3.6.4. Drones and Unmanned Aerial Vehicles (UAV)

While unmanned aerial vehicles (UAV), especially drones, have been widely employed in military missions and for intelligence gathering, their use in agriculture is exploding. Relatively inexpensive and reasonably simple to operate, drones can be equipped with sensors, cameras, and specialised hardware to perform a large array of functions in agriculture. Equipped with appropriate devices, drones are: (i) used to develop high-definition maps of fields that provide an ability to create prescriptive-defined application of sprays, fertiliser, pesticides, and herbicides, (ii) used to count the number of plants, fruits and flowers to forecast yields; (iii) employed to distribute seeds for crop planting; (iv) used when equipped with multispectral, hyperspectral and thermal cameras to measure chlorophyll, crop biomass, and plant health, as well as determine ground temperature, plant numbers, soil water content, and estimate crop yields; (v) a potential way to deliver contraceptives to manage wild horse and burro population; (vi) used to monitor a plant water stress and control irrigation so as to efficiently use water; (vii) used as 'nanobees' (miniature drones) should normal bee pollinators be absent or of an inadequate number to supplement the pollination process; (viii) used in outdoor livestock systems to monitor animals for estrus behaviour as well as control and manage the herd; and (xi) employed to monitor and track animals in inaccessible areas in the natural environment. In some countries, such as China, they might be used to spray pesticides, while this might be prohibited in other countries.

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[144] Future Farming. 2022. A website with contining information frequent updates in racking electric autonomous equipment, including tractors. https.www.futurefarming.com

[145] Malabo-Montpellier Panel. 2018. https://www.mamopanel.org/resources/mechanization/reports-and-briefings/summary-mechanized-transforming-africas-agricultur/

3.6.5. Biotechnology

The impacts of crop biotechnology have been studied over a 22-year period (1996-2018) on farm income and production[146] and on the environment[147]. Significant economic benefits at the farm level are globally estimated at USD 18.9 billion in 2018 and USD 225 billion (in nominal terms) for the 22 year-period. These gains are attributed at 52% to farmers in developing countries and 48% in developed countries with 72% of the gains based on yield and production increases and 28% from cost savings[146]. Returns on investment in genetically modified (GM) crop seeds were calculated at an average of USD 4.41 per dollar invested in developing countries and USD 3.24 per dollar invested in developed countries.

Assessments of environmental impact of GM crops estimate the use of global crop protection products to be reduced by 8.6% over this 22-year period. Reduced GHG emissions, through the adoption of reduced tillage, as it curtails fuel usage and improves soil carbon retention, are estimated to reduce the environemental impact by 19%. However, no-till management on croplands has become a controversial approach for storing carbon in soil due to conflicting findings[148].

The annual report of the International Service for the Acquisition of Agri-biotech Applications (ISAAA) provides a yearly global update on the adoption and distribution of biotech crops[149]. The 2019 report shows that GM crops increased in 29 countries with 190.4 billion hectares. A total of 72 countries have adopted biotech crops, with 29 having planted crops and 43 additional countries importing biotech crops for food, feed, and processing.

The biological world in 2020 was marked by CRISPR technology receiving recognition through the Nobel Prize in Chemistry awarded to its inventors. Simply stated, CRISPR is a unique technology used to edit selected genes by finding a specific bit of DNA inside a cell and altering it. Already applied in human health, it is being used in plant science for traits that can prevent disease, create pest resistance, increase resiliency, and improve crop yields.

Animal biotechnology has greatly contributed to the increasing of livestock productivity by ramping up production, reproductive efficiency, genetic improvement, animal nutrition, and animal health[150]. More specifically, recombinant bovine somatotropin (rBST) has been shown to increase feed conversion and milk yield. Major advances in animal reproduction have been experienced with biotechnology applied to genetics and breeding. The U.S. Food and Drug Administration approved in December 2020 a first-of-its-kind Intentional Genomic Alteration (IGA) in domestic pigs for food or human therapeutics[151].

However, as shown by the HLPE (2019, see Box 2), “despite the uptake of Genetically Modified technology, debates continue to be polarised and there are public concerns about safety, potential negative environmental impacts, resistance to corporatisation of agriculture and concerns about the ethics of gene modification”.

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[146] Brookes, G. and Barfoot, P. 2020a. GM crop technology use 1996-2018: farm income and production impacts. GM Crops and Foods 11(4). https://doi.org/10.1080/21645698.2020.1779574

[147] Brookes, G., Barfoot, P. 2020b. Environmental impacts of genetically modified (GM) crop use 1996-2018: impacts on pesticide use and carbon emissions. GM Crops and Foods.11(4). https://doi.org/10.1080/21645698.2020.1773198

[148] Ogle, S., Alsaker. C., Baldock. J., Bernoux, M., Breidt, F., McConkey, B., Regina, K., Vazquez-Amabile, G. 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci Rep 9, 11665 (2019). https://doi.org/10.1038/s41598-019-47861-7

[149] ISAAA. (International Service for the Acquisition of Agri-Biotech Applications). 2020. ISAAA Brief 55-2019: Global status of biotech crops. 2020. www.isaaa.org

[150] Tonamo, A., 2015. Review status of animal biotechnology and options for improving animal production in developing countries. 2015. J. of Biology, Agriculture and Healthcare. 5(19): 21- 31. ISSN 2225-093X

[151] FDA (Food and Drug Administration). 2020. Press Release December 14, 2020. Approves First-of-its-Kind Intentional Genomic Alteration in Line of Domestic Pigs for Both Human Food, Potential Therapeutic Uses

Box 2. The controversial issue of Genetically Modified technology as an example to addressing sustainability concerns (Source: HLPE 2019)

"There clearly needs to be more investment in agriculture and food research, including in careful assessment of modern biotechnologies, for improving food and nutritional security and delivering sustainable food systems in the wake of climate variability and change… On a global scale, the products of modern biotechnologies will be part of the transition towards Sustainable Food Systems… They are already a significant component of the agricultural systems in a number of countries… Recent calls for a global observatory for gene editing propose increased scrutiny, dialogue and deliberation on the use of modern biotechnologies…" p 80)

"Looking across the… controversial issues, it is possible to identify knowledge gaps around specific metrics of food system performance required to guide food system transitions and to clarify critical decisions that need to be made, including opportunities for reformulating the controversial issues towards the design of solutions on the one hand, or political choices among divergent views on the other" (p 18)

3.6.6. Nanotechnology

Nanoscale science and engineering offers the potential to significantly revolutionise the FAS. It can play an important role at each point along the FAS supply chain from production through consumption, including in the management of food losses and waste[152, 153]. In broad terms, nanotechnology can be a key element in the: (i) "re-engineering" of crops, animals, microbes, and other living systems at the genetic and cellular level; (ii) development of efficient, "smart" and self-replicating production technologies and inputs; (iii) development of tools and systems for identification, tracking and monitoring; and (iv) manufacture of new materials and modified crops, animals and food products.

The major part of advancement in the applications of nanotechnology in the FAS has largely occurred since 2000. Areas of application include food quality and safety, animal health monitoring and management, plant systems, environmental systems, and the assessment of societal impacts. Here are just a few applications: (i) nanomaterials for crop and animal disease detection and the detection of residues, trace chemicals, viruses, antibiotics and pathogens; (ii) the enhancement of plant nutrient uptake, nutrient use efficiency, and fertiliser efficiency by the controlled release of agrochemicals; (iii) seed coatings with nano-based chemicals to promote seed germination and deliver long-term disease and pathogen resistance; (iv) DNA-based genetic materials using DNA-based nano-barcodes with a multi-probe sensor to detect pathogens (in plants, animals and environmental contaminants); (v) the enhancement of water-use efficiency in crops by improving water retention and develop 'smart plants' to provide information on water needs and manage irrigation; and (vi) widespread advances in food packaging and food-contact materials for quality and increased shelf life.

Against this significant list of successful developments, nanotechnology's vision for the future is impressive[154, 155, 156, 157, 158] and includes among others: (i) the selectivity, robustness, ease of use, cost-effectiveness and longevity of nano-sensors as key components of the field-distributed, intelligent sensor network for monitoring and control and as part of the Internet of Agricultural Things (IoAT), (ii) the use of common field crops (e.g.,

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[152] Scott, N., Chen, H. Nanoscale science and engineering for agriculture and food systems. 2012. Industrial Biotechnology 8((6): 340-343. https//doi.org.10.1089/ind.2012.1549 (532-540) https://doi.org/10,1038 s41565-0900439-5

[153] Scott, N., Chen, H., Cui, H. 2018. Nanotechnology applications and implications of agrochemicals toward sustainable agriculture and food systems. J. Agric. Food Chem. 66(26): 5451-6456. DOI:10.1021/acs.jafc.8b00964

[154] Scott, N., Chen, H., Cui, H. 2018. Nanotechnology applications and implications of agrochemicals toward sustainable agriculture and food systems. J. Agric. Food Chem. 66(26): 5451-6456. DOI:10.1021/acs.jafc.8b00964; Giraldo et.al., 2019; Lew et.al., 2020; Gillbertson et.al., 2020; Kah et al., 2019.

[155] Giraldo, J., Wu, H., Newkirk, G. Kruss, S. 2019. Nanobiotechnology approaches for engineering smart plant sensors. Nature Biotechnology. 14 (541-553) https://doi.org/10.1038/s41565=019-0470-6

[156] Lew, T., Sarojam, R., Jang, I, Park, B., Naqvi, N., Wong, M., Singh, G., Ram, R., Shoseyov, O., Saito, K., Chua, N., Strano, . 2020 M. Species-independent analytical tools for next generation agriculture. Nature Plants. 6 (1408-1417) https://doi.org/10.1038/s41477-020-00808-7

[157] Gilbertson, L., Pourzahedi, L., Laughton, S., Gao, X., Zimmerman, J., Theis, T., Westerhoff, P. Lowry, G., 2020. Guiding the design space for nanotechnology to advance sustainable crop production. Nature Nanotechnology. https://doi.org/10.1038/s41565-020-0706-5

[158] Kah, M., Tufenkji, N., White, J. 2020. Nano-enabled strategies to enhance crop nutrition and protection. Nature Nanotechnology. 14(532-540). https://doi.org/10.1038/s41565-019-0439-5

corn, soybean, and grains) and trees to make sustainable chemicals; (iii) the design of nitrogen-producing microbiome and seed coatings that promote crops to produce their own nitrogen fertiliser; (iv) systems tracking the integrity of food (plant and animal) from production, transport, and storage to consumer consumption; (v) unique sensors: ingestible ones to monitor gut health, tooth sensors to measure food properties, or even chopsticks to detect food characteristics including nutrients; (vi) DNA lifelike materials from agricultural biomass, ranging from biosensors to biomanufacturing (replacing petrochemicals), to the development of value-added products including plastics that are biodegradable.

As in the case of biotechnology, some concern and socio-technical controversies have been expressed about health, environment, and social side-effects. This might be illustrated by the presence of nanoparticles in foods and their consequences for food safety. The EU has for instance banned the use of titanium dioxide in food.

3.6.7. Cross-cutting technology related observations

Technology played a pivotal role in the impressive agricultural transformation that took place in the 20th century and contributed to the increase and diversity of food supply despite demographic transition. Similarly, technology should play an essential role in addressing current and future sustainability challenges that bring together agriculture, food, health, energy, climate, environment, and social justice.

If technology should be considered a necessary and useful resource, there is no magic bullet, nor ‘one size fits all’ solution. Any technology may offer potential avenues for progress and provide benefits, but also bring about drawbacks and contribute to the emergence of new problems. In addition, the profound changes that are required will depend on a series of many complementary solutions, as no single one might address the breadth and depth of this challenge. These basic assumptions have two consequences.

They first call for the need to generate appropriate metrics and assessments that account for the capacity of technology to contribute, not only to decarbonisation, but also to all dimensions of sustainability as there might be trade-offs among them. This is neither trivial nor easy, as most assessments are context- as well as time- and space-scale specific, account for complex and uncertain processes, and require methods and indicators that are not always available. This is in particular the case for addressing emerging issues that were not considered in the past, in particular climate change.

The second consequence refers to the need for context-specific design processes. This is essential to jointly consider technological resources, the innovation process and their contributions to addressing sustainability concerns. Agricultural and food systems are context-specific. Their transformation relies on local adapted practice changes that depend on resources and available technology, know-how, risk management, etc., and may involve various stakeholders with divergent vested interests. In addition to discussions on its impact, technology implementation may thus face resistance related to values and interests, conflicts of interest, risk management and path dependency[159] that make it very complex to analyse its political economy.

Finally, technology may have a controversial dimension and, alongside growing suspicion concerning technology and the spread of fake news, may become a polemical and polarising issue, as the well-known and documented case for Genetically Modified Organisms shows. In order to understand and consider controversies related to agroecology, the HLPE for example identified divergent views and values regarding 6 topics that were analysed taking into consideration governance, economic, resource, social, cultural and knowledge factors.

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[159] HLPE. 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from https://www.fao.org/3/i7846e/i7846e.pdf

4. Different narratives

The transformation of food systems will take place considering four sets of driving and steering forces. The first set will depend upon the type of technology that is promoted and the economic model it refers to and serves. We can in particular foresee three differentiated and simultaneous trends: (i) the acceleration of technology, which is intensive in capital, adapted to large-scale production or industrial units and contributes to economies of scale; (ii) high tech development, implemented by start-ups and small and agile production units that permanently adapt to the market and constitute themselves in economic clusters; (iii) the advance of low-tech green and circular systems that favour local informal chains based on proximity and resource recycling.

The second set is related to the capacity of technology to ensure production independently from land use: it will be a key driver in the future to address environmental issues, although the energy consumption of such modalities will be key to alleviating the environment footprint.

The third set is about what we shall produce and will depend on what we will consume and waste. The share of animal source products in consumption will be key and the young generation is likely to engage and promote deep changes in consumption patterns.

The fourth set for the transformation will depend on the capacity or not to promote the co-existence of different food systems, building upon synergies and complementarities at territorial and regional levels as a way to ensure adaptability, resilience, and sustainability. This relates to agricultural production and the way land use takes into account environmental concerns through landscape symbiosis that address the artificial opposition between options represented by land sharing and land sparing (see section 4). This also relates to the agro-industrial sector with the development of territorial symbiosis or of specialised production basins.

These four sets will shape the future of food systems, and, as a consequence their contribution to decarbonisation, their performance regarding energy production and consumption and their environment footprint, including their contribution to climate change. Among plausible and possible futures, when considering the two axis of “Degradation versus sustainability” and “Regional versus global” at the global level, we could for example imagine:

- the general collapse of food systems because of their high and uniform specialisation and, as a consequence, their low resistance to shocks;
- a differentiated transformation in which sustainable production “pockets” emerge and become the regional or global cellar, while the food production capacity of other regions is completely degraded;
- a balanced organisation of sustainable food systems based on territorial symbiosis and connected to each other through efficient global regulation mechanisms;
- an archipelago of local sustainable food systems with little exchanges.

Further research is needed to prepare the methods, metrics, and equipment to assess such an evolution.

5. Key messages and recommendations

A large panel of technologies is available to act on the decarbonisation of food and agriculture systems (FAS). The following key messages summarise our main recommendations toward this end. Yet, because of the complex, multidimensional and interscale interactions of the FAS transformation, knowledge is still missing to steer desirable pathways.

Key Messages

5.1. Major transformations

The Food and agriculture systems (FAS) have gone through deep transformations to cope with the huge demographic transition and feed the world. Although the required increase in production has been achieved, this transformation generated sustainability concerns, which in turn call again for radical change. This need is reinforced by global changes (climate change, conflicts and wars, etc.) that will dramatically impact food, agriculture, and ecosystems around the world.

5.2. Decarbonisation and methane reduction

Decarbonisation and methane reduction are essential components in this transformation but not the only ones. This implies trade-offs among diverging sustainability objectives and across time and space scales, and calls for the strengthening of our capacity to address such trade-offs through evidence and arbitration mechanisms; a nexus approach and specific mechanisms are needed to address controversies and arbitrate contradictions at all levels, including between local innovations and global challenges.

5.3. Disruptive technologies and behaviour

There are now strong driving and steering forces fostering the transformation of the FAS, including calls for significant change and reduction in the consumption of animal-based foods from the young generation to a healthier diet with less meat; yet there is much controversy, in particular regarding the mobilisation of disruptive technologies because of entrenched long-standing traditional practices, together with the association of food with religious and cultural dimensions, on the one hand, and the increasing concentration in the agri-food sector on the other hand.

5.4. System of systems

The FAS is a system of systems and thus systems thinking is critical to transform the FAS towards meeting sustainable development goals; *however, it is the people who will make it happen – or not*. To that end, there is need to move beyond contentious debates, acknowledge the social, cultural, economic and political dimensions of problems and solutions, and accept and design a broad array of approaches valuing scientific evidence as much as possible.

5.5. Advances in science and technology including design and metrics

Science and technology were keys in generating the past transformation of the food systems and will continue to play an eminent role; yet their impact can be either negative or positive, and innovation does not always contribute to sustainable development. While, in the past, the performance criteria of both technology and innovation in the FAS mainly relied on productivity and economic competitiveness, today, addressing future challenges requires new assessment methods, criteria, and metrics; this not only applies to the agricultural production, but also to the whole food system; this is needed to promote decarbonisation and address trade-offs towards sustainability.

5.6. Quantitative impact of specific technologies

There is a need to assess the potential contributions of specific technologies for decarbonisation. However, this very much depends on each specific ecological, technological and social context, on the one hand, and on the way each technology is implemented on the other hand. Such knowledge is rarely available today and this would need a strong investment in research and expertise.

5.7. Stable Public Policies

Stable and comprehensive public policies are needed to make sure technology and innovation contribute to decarbonisation; this includes in particular trade agreements, intellectual property rights, market regulation, taxes, and subsidies.

5.8. Need for research and extension

Research is required to design and transfer technology and information to all stakeholders including farmers, processors, consumers, extension/outreach persons, and policy makers at all levels of government from the global to the local. Research is also needed to foster participation and innovation arragements to identify drivers and obstacles to innovation, and assess contributions to decarbonisation participate in innovation arrangements, identify drivers and obstacles to innovation, and assess contributions to decarbonisation.

Recommendations

5.9. Food supply chain

We recommend that science and technology innovations for decarbonisation receive increased emphasis for development at all stages of the FAS from pre-production inputs, through food production, processing, packaging, distribution and consumption, to waste management.

5.10. Methane reduction

We recommend that pathways be further developed to reduce biogenic methane from livestock and rice cultivation. New feeds, feed additives, improvements in manure management, etc. are needed to significantly reduce methane emissions from ruminant livestock. Improvements in irrigation techniques, increased efficiency in the use of fertilisers, new rice varieties and the potential use of bacteria in the field should improve, so as to address the issue of reducing the share of methane in the rice fields.

5.11. Energy efficiency and decarbonisation

We recommend that energy efficiency and conservation practices be top priorities along the supply chain ‘from farm to fork’, because direct and indirect energy savings drive decarbonisation. We recommend to increase developments in the co-location of solar Photovoltaics, ‘agrivoltaics’ and wind turbines on agriculture land. We also recommend electrification across the food supply chain from field equipment (tractors), food processing, storage, transportation, to consumption.

5.12. Alternative protein foods / Controlled environment agriculture

We recommend the application of Life Cycle Assessment studies to assess any reported environmental benefits of alternative protein foods, 3D-printed foods, aquaculture / aquaponic systems, and advanced greenhouses including vertical farms to quantify this potential transition to a healthier diet that includes less traditional meat and significant benefits for decarbonisation.

5.13. Circular economy

We recommend that the FAS adopt and apply the principles of circularity as a key strategy to address the reduction of food loss and waste along the food supply chain from ‘farm to fork’.

5.14. Biomass / Bioenergy

We recommend restricting the utilisation of biomass for bioenergy, biofuels, and biochar to situations that do not compete with land use for food crops and that do not generate price volatility and food insecurity. Furthermore, biogas produced from waste organic sources can be an important driver of combined heat and power systems at farm, community and district levels.

5.15. Biotechnology

We recommend the adoption of biotechnology in the FAS when improved performance also contributes to lowering GHG emissions as less fossil fuel is being used and to reducing the amount and use of disease protection products.

5.16. Nanotechnology

We recommend the adoption of nanotechnology when it contributes to addressing decarbonisation, examples of which include biomanufacturing to replace petroleum-based products, seed coatings to enhance nutrient uptakes, more efficient uptakes of nitrogen fertilisers that may reduce the amount of nitrogen (N) needed and curtail N losses, and the development of safe edible packaging, to only mention a few.

5.17. Nitrogen use efficiency

We recommend the right application of N-fertiliser use through practices that enhance nitrogen use efficiency: the right N source, right rate, right time of application, and right placement. Depending on the context, this could lead to an increase or a reduction through, for example, integrated soil management approaches, precision agriculture for placement and nanotechnology for time release.

5.18. Regenerative agriculture / Agroecology / Agroforestry

We recommend the initiation of in-depth studies to quantify expectations that these practices sequester soil carbon and also enhance soil health. This is important to develop public incentives and a rational and equitable carbon market for farmers.

5.19. Digital Agriculture

We recommend the continued assessment of decarbonisation resulting from Digital Agriculture. Digital agriculture is a marriage of seemingly disparate technologies involving advanced sensors, artificial intelligence, data integration, big data, drones, robots, nanotechnology, smart food packaging, electronic devices (computers, tablets, smartphones), tracking technologies, and climate information that lead to sustainability in food production and processing.

5.20. Policy framework

We recommend the development of a facilitating policy framework and the implementation of adapted and context-specific policies to fully capture the benefits of science, engineering and innovation, while ensuring reduced inequality and the coordinated governance of land and oceans so that FAS may improve and gain in sustainability.

List of abbreviations and acronyms

CHP	Combined Heat and Power
CRISPR	Clustered Regularly Interspersed Short Palindromic Repeats
DNA	Deoxyribonucleic Acid
EU	European Union
EGS	Enhanced Geothermal Systems
FAS	Food and Agriculture System
FLW	Food Loss and Waste
GM	Genetically Modified
GHG	Greenhouse Gas
HLPE/CFS	High-Level Panel of Experts of the UN Committee on World Food Security
HPC	High Performance Computing
IGA	Intentional Genomic Alteration
IoAT	Agricultural Internet of Things
IPCC	International Panel on Climate Change
LCA	Life cycle Assessment
LULUC	Land use and land use change
MIMO	Multiple Input-Multiple Output
NFU	National Farmers’ Union
OECD	Organisation for Economic Co-operation and Development
NRC	National Research Council
PAR	Photosynthetic Active Radiation
RNG	Renewable Natural Gas
SDG	Sustainable Development Goal
TEA	Techno-Economic Assessment
UAV	Unmanned Aerial Vehicles
UN	United Nations
VF	Vertical Farm