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ORIGINAL ARTICLE

CropBooster-P: Towards a roadmap for plant research to future-proof crops in Europe

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Abstract

The world needs more than double its current agricultural productivity by 2050 to produce enough food and feed, as well as to provide feedstock for the bio-economy. These future increases will not only need to be sustainable but without comprommising the nutritional quality, and ideally also need to decrease greenhouse gas emissions and increase carbon sequestration to help mitigate the consequences of global climate change. These challenges could be tackled by developing and integrating new future-proof crops into our food system. The H2020 CropBooster-P project sets out plant-centered breeding approaches guided by a broad socio-economic and societal support. First, the potential approaches for breeding crops with sustainably increased yields adapted to the future climate of Europe are identified. These crop-breeding options are subsequently prioritized and their adoption considered by experts across the agri-food system and the wider public, taking into account environmental, economic and other technical criteria. In this way, a specific research agenda to future-proof our crops was developed, supported by an eventual implementation plan.

KEYWORDS

climate change, crop improvement, crop yield, food supply, H2020, nutritional quality, sustainability

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1 | INTRODUCTION

To sustainably meet our projected future food requirements and growth of the bioeconomy as we transition away from fossil fuels (Fritsche et al., 2020), more crops will need to be produced on the same or even a smaller area of arable land, without compromising nutritional quality if we are to provide healthy and sufficient food for all (Harbinson et al., 2021). Therefore, there is a need for higher yielding crops that show an increased resilience (crop sustainability), so with more efficient use of scarce resources, including water and minerals, and that are suited to cultivation schemes and practices that preserve biodiversity. We also need to minimize the environmental impact of agriculture to increase 'carbon smartness' (the European 'Green Deal'), and increase the use of soil carbon and wood to sequester atmospheric carbon dioxide to mitigate the effects of climate change, something to which agriculture and silviculture could potentially make an important contribution (Harbinson et al., 2021; Martin et al., 2021; Rumpel et al., 2020). Increasing the soil carbon pool of agricultural land will not only provide a sink for atmospheric carbon dioxide but will also improve the agricultural properties of the soil (McBratney et al., 2014). In addition, the climate and environmental changes we are currently experiencing, e.g., increasing summer drought or high temperatures in the Mediterranean region, as well as in other regions of Europe (Webber et al., 2018), present a challenge to our current crop cultivation models. The projections made so far of the influence of climate change combined with increased atmospheric carbon dioxide levels on crop productivity show diverse effects (Rivero et al., 2021; Sinha et al., 2021). For example, winter wheat will tend to benefit from warmer springs with increase in yield, whereas summer drought will decrease maize yields (Webber et al., 2018). In addition, crop productivity will decrease by the increased frequency of extreme events due to climate change, i.e., hot and cold snaps, drought and flooding. These effects will occur even in the milder, wetter northwestern oceanic regions of Europe (Webber et al., 2018). Our crops must therefore not only very efficiently use agricultural resources, such as water and nitrogen, but also have a high resilience to adverse and volatile weather conditions to obtain high and stable yields in our future climate. To help meet these productivity and nutritional challenges, our current crop plants need to be adapted in multiple ways and thus mapping the route to future-proof our crops has become a matter of urgency. Here, we aim to present a high-level overview of the scope of the CropBooster-P project, how the project is structured/organized in different work packages (WPs), what the goal is of each of these WPs, how all the parts of the project are interconnected, and to refer to and present in brief some of the project results.

2 | THE CROPBOOSTER-P PROJECT

The H2020 CropBooster-P project is a research initiative led by a consortium of European universities and research institutes to prepare a roadmap for the development of improved crops to future-proof European agriculture (Harbinson et al., 2021) (https://www.cropbooster-p.eu/). For this, a concerted plant breeding perspective is being developed that has a broad socio-economic and societal support.

To support the creation of this roadmap, the CropBooster-P project had five work packages (WPs), each with their own goal (Figure 1): developing a research toolbox (WP1), prioritizing and analyzing the adoption of the research toolbox by expert consultation (WP2), engaging with different societal actors and anticipating their perspectives (WP3), facilitating international engagement and cooperation (WP4) and generating a roadmap, consisting of a research agenda and an implementation plan (WP5), taking into account the outcomes and recommendations from the previous work packages, to future-proof our crops and communicate about this to the public at large (WP6). In this way, we could identify and recommend routes for the future development of crops that would meet future food and sustainability challenges in ways that are most beneficial to, and accepted by, society.

3 | CROPBOOSTER-P RESEARCH TOOLBOX DEVELOPMENT

In WP1, the project analyzed the available tools (technologies and traits) to improve crops. The project first identified both major and underutilized terrestrial and aquatic crop species and generated a comprehensive evaluation of the most promising currently available technologies and practical approaches to improve these crops. Following traits were aspired for crop improvement: yield (Burgess et al., 2022), nutritional quality (Scharff et al., 2021) and sustainability (Gojon et al., 2022) (see Definition Box). The genetic basis for crop improvement can be addressed by both conventional breeding and biotechnological methods. These methods encompass all modern plant breeding approaches, such as marker-assisted selection/breeding (MAS/MAB) or genome-assisted selection, as well

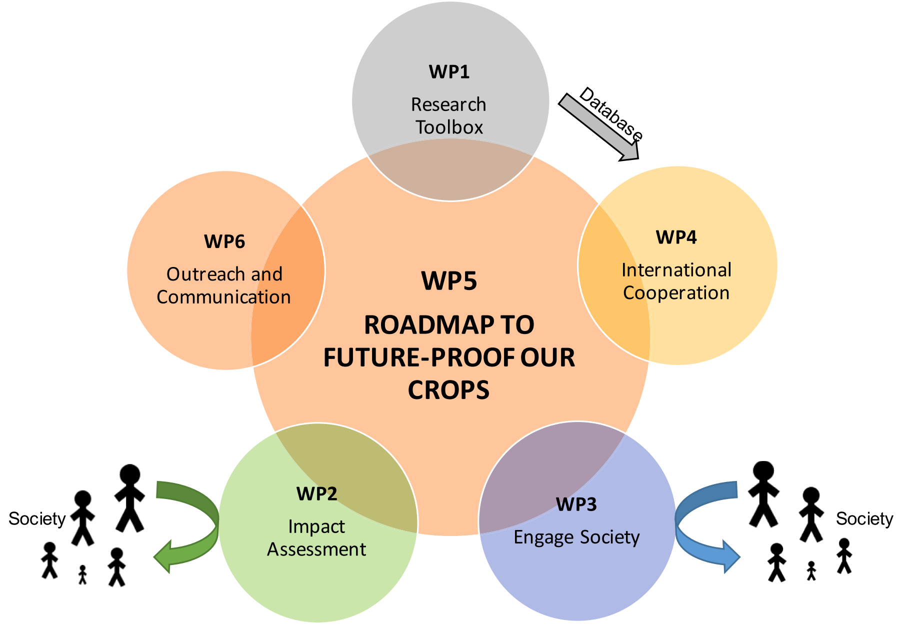

FIGURE 1 Modular overview of the CropBooster-P project. The project is subdivided in six work packages (WPs).

as advanced breeding technologies and novel DNA mutagenesis technologies such as CRISPR/Cas, gene transfer technologies, and synthetic biology approaches, in which complete novel metabolic and/or genetic pathways are transferred. While fully acknowledging that achieving the desired crop productivity demands will concern all aspects of the agricultural system, technical options to improve crop management or optimization of agricultural practices are not in the scope of the project—our main focus is on improving crops themselves.

To breed crops adapted to the future climate of Europe, potential approaches were identified within WP1 that may result in crops with a sustainably increased yield without compromising or even improving nutritional quality (WP1: 'Research toolbox') (Burgess et al., 2022; Gojon et al., 2022; Scharff et al., 2021). Crops will need to be more stress-tolerant and more resilient to environmental constraints, ensuring a better adaption to and/or faster recovery from suboptimal growth conditions. To compile a toolbox outlining transferable strategies, methods and technologies to sustainably improve crop productivity, a panel of experts with a broad range of specializations in diverse areas of crop biology and production has been identified to maximally assure an adequate representation of the various aspects of crop growth and productivity. These experts have been asked to identify up to 15 key publications outlining current scientific state-of-the-art techniques, advanced breeding methods and potential strategies for crop improvement with a focus on plant traits that are by implication heritable and/or transferable and can be exploited to increase plant yield potential, yield stability and/or nutritional quality. A further emphasis was made on species that serve as model plant species, species with major agricultural value and species that are already important in Europe to meet the future crop productivity needs (see Crop Selection Box). Subsequently, a literature survey and database have been developed, making this information on plant traits, technologies, genes and methods exploitable (https://cropbooster-p.wur.nl). In addition, an effort has been made to capture existing knowledge about studies on underutilized terrestrial crops and marine macrophytes (seaweeds). Within the database construction, each publication entry is accompanied by a survey capturing in detail the determinants of the different traits. For example, the data collection for a publication regarding nutritional quality could run as follows (Figure 2): selection of the nutrient class (e.g., proteins, vitamins or minerals), further specification of categories and subcategories (e.g., macronutrients, micronutrients or specific nutrients) and finally collection of the physical and/or environmental factors affecting this trait. The experts could indicate whether the gene/trait under consideration affected multiple plant determinants, e.g., a gene or pathway that has an impact on both nutritional quality and yield potential. In this way, it is possible to identify trends and commonalities between multiple database entries, identified traits and specified technologies. With the help of the database, several key opportunities to improve crop production and quality have been identified (Baekelandt et al., 2022; Burgess et al., 2022; Gojon et al., 2022; Scharff et al., 2021), e.g., exploring the wild germplasm of crops for desirable traits, investigating alternative protein sources using non-traditional and ancient grain species, and reducing or even eliminating antinutritional factors in plants by means of biotechnological approaches.

Definition Box

Yield refers at first instance to the total amount of crop biomass produced per unit area per year. In many cases, this will refer only to above-ground biomass, with the exception of below-ground storage organs (e.g., potatoes and sugar beet) since below-ground biomass is often not commercially harvested and is difficult to quantify. In many cases, a crop plant is not cultured throughout the entire year but only during its specific growing season, so a yield increase could be achieved by having the same growth rate in a longer growing season, or increasing the growth rate with no change in growing season, or both. Producing the same yield in less time could allow more than one harvest per year. Increasing yield thus encompasses all breeding options to develop plants, both terrestrial and aquatic, that increase the total productive potential per hectare per year. This definition of yield is valid especially for plants that are biomass for non-food applications and are generally harvested as total above-ground plant biomass. For food and some non-food applications (e.g., wheat, cotton), an additional constraint for yield applies because only part of the (above-ground) plant biomass will have any significant post-harvest use. Many crop plants are grown as resources of raw materials for further refinement to produce specific products, such as sugar, starches, protein and secondary metabolites. Increasing productivity for these materials is also a valid yield increase and an important function of agriculture.

For food crops, quality refers to the **nutritional quality** of the edible plant parts. Increasing quality thus entails all breeding options that result in an increase in, among others, protein content, mineral content and fatty acid content. In our definition, organoleptic (taste, smell, mouth-feeling) properties are out of scope. Although they are recognized as important to meet the consumer preferences and food choices, these quality aspects are not considered as crucial to safeguard future food security. For non-food purposes, quality refers to plant characteristics that determine the suitability or value of the crop for its specific application, for instance the fibre digestibility of animal feed, the fibre quality for industry, or the oil content.

In the CropBooster-P project, we address three aspects of **sustainability**: crop sustainability, societal sustainability and economic sustainability. Crop sustainability relates to plant properties that increase tolerance to climate change, such as abiotic stress resistance, resilience and/or acclimation capacity, and to resource use efficiency, especially water and mineral nutrients. Increasing sustainability encompasses all breeding options to increase the resistance of our crops against abiotic stresses such as heat, freezing and water management including drought, salinity and flooding. For reasons of capacity, biotic stress resistance is out of scope of the CropBooster-P project. Societal sustainability relates to the societal acceptability of the goals of the program, and economic sustainability to the profitability of the future crop models we envisage to be produced.

Crop Selection Box

Algae *Laminaria*, *Porphyra*, *Ulva lactuca****Forage grasses*** *Lolium perenne* (ryegrass), *Medicago sativa* (alfalfa)***Grain staples*** *Triticum aestivum* (wheat), *Zea mays* (maize)***N_2 fixers*** *Glycine max* (soybean), *Pisum sativum* (pea)***Oilseed*** *Helianthus annuus* (sunflower), *Brassica rapa* (rapeseed)***Vegetables*** *Solanum lycopersicum* (tomato), *Lactuca sativa* (lettuce)***Fibre and lignocellulosic crops*** *Populus* (poplar), *Miscanthus sinensis* (miscanthus)***Root staples*** *Solanum tuberosum* (potato), *Beta vulgaris* (sugar beet)***Model plants*** *Arabidopsis thaliana* (arabidopsis), *Nicotiana tabacum* (tobacco)***Others (e.g., fruits)*** *Vitis vinifera* (grape), Pome fruits.

Crop species selection includes species distributed in ten main classes (in bold). The example crops presented here, for each crop category, were considered priority crops for the CropBooster-P data collection.

Finally, the panel of experts belonging to participant institutions from the CropBooster-P consortium, ensuring a broad representation of knowledge about species, research fields, approaches and technologies, have queried

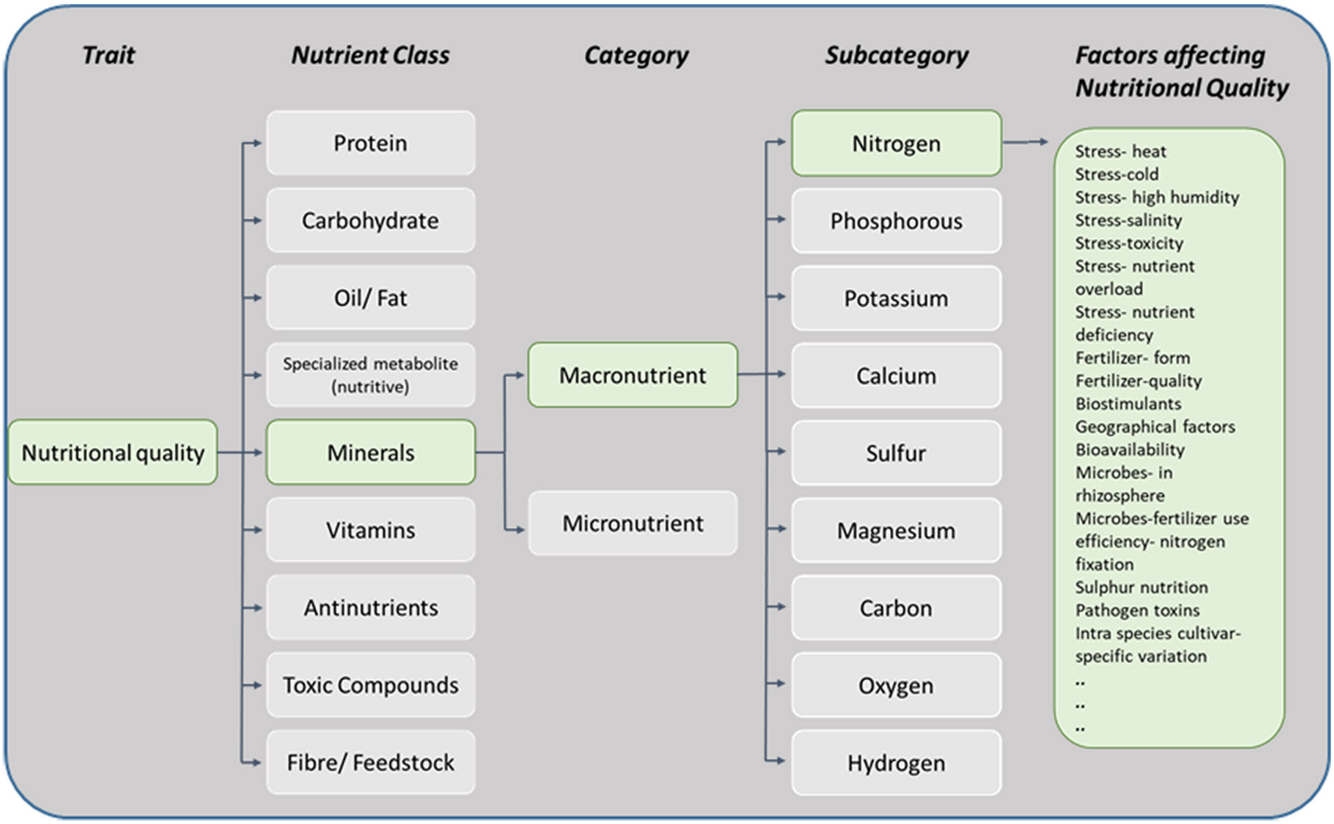

FIGURE 2 Example of different levels specific to nutritional quality. A detailed list of determinants of yield, crop sustainability and nutritional quality can be found on https://www.cropbooster-p.eu/.

the database. This already resulted in several reviews describing relevant genes, traits and technologies of interest and presenting a prospective view on breeding options that could be exploited in distinct research fields with respect to crop improvement (Baekelandt et al., 2022; Burgess et al., 2022; Gojon et al., 2022; Scharff et al., 2021). These are, however, only the tip of the iceberg, and the flexibility of the database allows to further extract specific information, such as which traits have been underexplored in which crop species, as well as reveal useful connections across species and plant traits, e.g., with regard to the role of specific genes in multiple plant developmental processes.

The CropBooster-P database can therefore be considered as an expert resource including recent advances and/or key findings with regard to traits that have been successfully selected/changed and that could contribute to the future-proofing of our crops in terms of increasing plant yield, sustainability and nutritional quality. Within the project, the database served as a foundation because it is both a scientifically sound overview of the current state-of-the-art in distinct research fields, as well as a resource with which to engage in discussion with stakeholder groups (Nair et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Duchesne, et al., 2022) and the general public in later phases of the CropBooster-P project.

4 | TOWARDS THE CROPBOOSTER-P ROADMAP

The future requirements for our crops are diverse and demanding, requiring significant increases in crop productivity if we are first to ensure future food and nutritional security, second to facilitate the transitioning to a non-fossil carbon economy, third to allow a more sustainable agriculture, and fourth to contribute to the reduction of atmospheric carbon dioxide. To do so, crop yield should be increased, while decreasing the input per unit yield. In this way, we can improve crop productivity on our existing area of agricultural land and do so in a more sustainable, resource-efficient way. To meet these aspirational future demands, our current crop plants will need to be adapted, and mapping out a long-term strategy for future-proofing our crops is thus urgently needed. Progress to improve crop productivity is, however, mired in the complexity of the multitude of possible crops, traits and genetic changes, combined with multiple technical, environmental, policy and societal challenges.

Within the H2020 CropBooster-P project, a roadmap was developed to guide future plant research to improve crop productivity in Europe (Harbinson et al., 2021). In parallel to the development of the research toolbox (WP1), the project has set out possible scenarios of future situations for which our future-proofed crops would need to be developed and the possible regulatory or societal constraints that may limit that development (Cornelissen et al., 2021). For this, a multitude of trends and key uncertainties were identified and analyzed as the basis for the scenario planning. The trends that were included range from consumer behavior and demographics, to farming and technology, politics, economy, and societal developments (Cornelissen et al., 2021). In addition, uncertainties were identified and clustered around three themes: the need for adaptation, the priorities in the value chain, and the role of science. This analysis resulted in four contrasting scenarios for Europe's food and bioeconomy future, which will be taken into account when generating the roadmap: '*Bio-Innovation*', '*My Choice*', '*Food Emergency*' and '*REJECTech*' (Baekelandt et al., 2022; Cornelissen et al., 2021) (Figure 3). The four possible future scenarios that have been developed were used more downstream in the CropBooster-P project (Baekelandt et al., 2022; Cornelissen et al., 2021) and were taken into account when generating the roadmap.

In parallel to the data collection, the identification of breeding options to improve crops and the development of future world scenarios, modeling analyses are performed using mechanistic and thoroughly understood models. The modeling approaches demonstrated how adjusting individual traits could significantly increase agricultural yields at different geographical locations in Europe, using the impact of an increased photosynthetic efficiency on yield for a number of key crops in Europe as a case study (Harbinson & Yin, 2022). Modeling has shown that crop yield increases in Europe of 17% for wheat and 24% for potato, and even more for total biomass, can be achieved with only 20% increases in some basic photosynthetic parameters (Harbinson & Yin, 2022). In the future, more complete crop models that incorporate a wider range of mechanisms and processes and recent innovations could enable better predictions about how the most promising approaches for increasing e.g., photosynthesis will function at crop scale.

To further explore the data collected and the traits identified in the database (WP1), and to facilitate the development of the roadmap (WP5), an exhaustive analysis of the literature has been carried out in WP4 ('International cooperation') and an in-depth inventory of the scientific productivity in distinct plant research fields has been made. These analyses made use of 24,000 publications retrieved from the WOS database (2015–2019) and provided an exhaustive view of the main actors (scientists and institutions) involved in these fields of research in Europe. A total of 15 focus group coordinators were then identified from these main institutions. To strengthen interactions between Europe's research institutions and between hubs of plant research in Europe, the coordinator of each focus group was asked to identify and contact experts with relevant scientific expertise in their respective fields. Each of these focus groups carefully evaluated a different subtopic of crop yield, sustainability and nutritional quality to add any information needed to reinforce, broaden and detail the current identified options for future crop

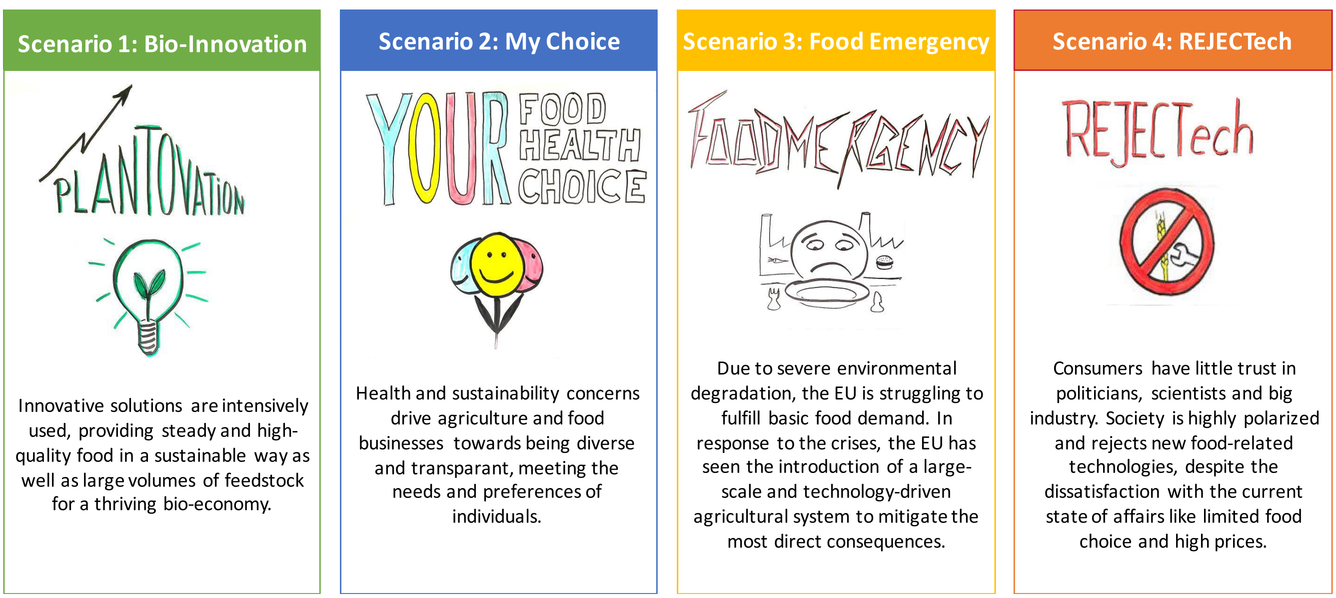

FIGURE 3 Outcome of the CropBooster-P project scenario analysis. Four learning scenarios were developed: '*Bio-Innovation*', '*My Choice*', '*Food Emergency*' and '*REJECTech*'.

improvement. More specifically, the ambition of each focus group was to propose strategic research actions that would be expected to contribute to reaching the EU strategic goals as outlined in the so-called 'Green Deal' and the 'Farm to Fork' concepts (presentations of the focus groups can be found in the "Project results" page of the CropBooster-P website; https://www.cropbooster-p.eu/the-project/presentations.html).

Having identified a suite of scientific and technological crop improvement options, their social, environmental and economic impacts were analyzed in WP2 ('Impact assessment') (Nair et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Duchesne, et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Guichaoua, et al., 2022). To prioritize the traits to select for to future-proof our crops and to identify and discuss the wider social, economic and environmental impacts of adopting these crop improvements, experts from farm-level to businesses and supply chains to the consumer have been consulted in a series of online workshops and surveys (Menary et al., 2021; Nair et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Duchesne, et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Guichaoua, et al., 2022).

Society must be involved in the decision-making process, because ensuring food and nutritional security, while at the same time mitigating the effects of global climate change and protecting biodiversity, will require a number of drastic measures, which will necessitate the support of the European society as a whole for successful implementation. To this end, WP3 ('Engage society') engaged the general public in a dialog about the need for crop improvement. For this, consumers and other non-expert lay people were engaged in a series of workshops and events to find out how the issues of the CropBooster-P project are perceived and identify the specific objectives of different societal groups (Nair et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Duchesne, et al., 2022; Stetkiewicz, Menary, Nair, Rufino, Fischer, Cornelissen, Guichaoua, et al., 2022). On the topic of crop improvement, participants ranked environmental sustainability traits, also referred to as traits underlying crop resilience, higher than those improving nutritional quality or only increasing yield. In addition, it was anticipated that the use of new plant breeding techniques seem to be (more) acceptable if they serve the needs identified with high priorities. Such a trend was previously also observed in a national survey conducted in Norway (Norwegian Biotechnology Advisory Board, 2020). A further goal of WP3 was to understand and advise how to best communicate complex scientific information to different societal groups, including the general public in Europe. For this, attitudes, expectations and appropriate means of communication were explored through questionnaires and interviews. These include aspects such as scientific research, plant breeding technology, food security, climate change and biodiversity, and the interconnections between these topics. The surveys underlined the importance of a dialogue between scientists/researchers and different stakeholder/societal groups to increase understanding and gain acceptance (Will et al., 2022). Moreover, they showed considerable differences between the various groups in relation to their preferential topics to communicate about in view of crop improvement and the use of modern breeding technologies. The diversity was even more pronounced for the means used for communication and gaining information: the preferences for the use of certain media channels may vary on a regional level even within a stakeholder group.

Finally, the project also developed a detailed research agenda and implementation plan in WP5 ('Roadmap to future-proof crops'). The roadmap lays out how the identified options for sustainable yield improvement can be implemented in a future plant research program, with the aim of providing innovative starting points for the breeding and the production of new cultivars. This roadmap was developed with both the European plant science community at large and the plant-breeding sector (Harbinson et al., 2022). To generate an action plan ensuring the broadest societal support and benefits, the four contrasting future world scenarios were taken into account (Cornelissen et al., 2021) (Figure 3). CropBooster-P devised a strategy for future-proofing Europe's plants and draft a research project to implement the possible options in each of the four future world scenarios (Baekelandt et al., 2022; Cornelissen et al., 2021). In this way, CropBooster-P offers a flexible and versatile contribution to future-proof global food and nutrition security that embodies the ambitions of the Paris Climate Agreement COP21, the European 'Green Deal' and many of the United Nation's sustainable development goals.

Summarizing, the CropBooster-P project contributed to identify and prioritize (1) which land-based and marine crop species have the potential to secure future food quality, diversity and quantity, (2) which crop traits are available and should be improved to sustainably produce high-quality biomass for food, feed and non-food purposes, (3) which breeding options and technologies are available and/or should be considered to meet the needs of future society and (4) how we can reach these goals. The key options that could be explored to improve crop productivity and/or quality were further discussed and developed in a series of stakeholder consultations, involving consumers, farmers, industry, policy-makers and networks of EU scientists, and the implications of the different future world scenarios were analyzed. The final conclusions of the CropBooster-P project were presented in the form of a roadmap that sets out the multi-actor approach required to develop Europe's future crops (Harbinson et al., 2022). This will allow plant science to integrate the innovations in the wider system and to ensure their broadest societal support and benefits possible.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study

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