



OPEN What farmers think about using crop biotechnology to boost photosynthesis in rice and potato

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Boosting crop photosynthesis holds promise for meeting the needs of a growing population in a warming climate. However, improving photosynthesis with crop biotechnology is a new prospect for farmers and other key agrifood stakeholders, who will determine the success of such pioneering plant breeding initiatives. We conducted focus groups with 62 participants in four countries to understand farmer and agrifood stakeholder perspectives towards the aim of boosting photosynthesis through biotechnology in rice and potato, two of the world's most important crops. We found farmers were positive towards the benefits of boosting photosynthesis, although the relative importance of improving yield was debated – water and radiation use efficiency were less contested and linked to more sustainable agriculture. Farmer concerns centered on balancing the competing agronomic and market demands that new varieties would bring. Farmers in the low-income countries had few concerns about the use of biotechnology and anchored their understanding in existing biotechnology crops, such as Golden Rice in the Philippines and Bt Brinjal in Bangladesh. Farmers in Europe and industry stakeholders were more apprehensive about biotechnology crops for several reasons that were rooted in the perceived opinion of consumers and supermarkets towards biotechnology.

Global agriculture must feed a growing population – increasing production 35–56% by 2050 – against a backdrop of climate change and other environmental impacts caused in part by its own intensification^{1,2}. Combinations of new tools and knowledge have created an opportunity for plant biologists to boost photosynthesis in C3 plants. The name “C3” refers to the three-carbon molecule that is the first stable product formed during their photosynthetic process. Together, C3 plants provide 90% of the carbohydrates produced on Earth³ and constitute some of the most important food crops such as wheat, rice and potatoes. Increased yield, improved water use efficiency and heat and drought stress tolerance are expected benefits of improving photosynthetic performance^{4,5}. Improving photosynthesis has been proposed by plant scientists as a means of connecting our understanding of crop biology with meaningful improvements in agriculture⁶.

The prospect of improved photosynthesis as a distinct breeding target is new for stakeholders involved in food production. However, there has been no research to date exploring the intersection of farmer and other agrifood stakeholder needs, crop improvement targeting photosynthesis and biotechnology. In this paper we use the responsible research and innovation (RRI) framework to guide stakeholder involvement in an EU project (PhotoBoost) in order to understand stakeholder attitudes towards both improved photosynthesis in crop plants and the use of crop biotechnology to achieve it. Below, we explain the current prospects for improved photosynthetic machinery in C3 plants and the reliance on biotechnology to achieve such a step change in plant productivity, before outlining the PhotoBoost project and how the RRI framework fits into the wider field of agricultural innovation studies.

Boosting photosynthesis

Substantial improvements in yield during the Green Revolution were driven by the incorporation of dwarfing genes into wheat and rice (alongside increasing use of agricultural inputs) and later through carbon allocation and early vigor. These dimensions of plant physiology are, today, already well optimised⁷. In 2006 Long et al.⁸

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asked whether increasing photosynthesis could increase yield: since that time, researchers have identified a number of “pathways” to improving C3 photosynthesis.

Photorespiration, a known issue in C3 plants is the first. The enzyme RuBisCO sometimes catalyses O₂ rather than CO₂, leading to the loss of freshly fixed CO₂ and the production of compounds that need to be reassimilated within the plant⁹. At present atmospheric concentrations of CO₂ and a temperature of 25°C, around 30% of fixed CO₂ is lost through photorespiration – higher temperatures lead to greater losses¹⁰. Although photorespiration is associated with other metabolic processes¹¹, providing a “bypass” using multigene assemblies (including from cyanobacteria and other bacterial species) can increase plant biomass^{12,13}. Such bypasses have been shown to increase yield in *Arabidopsis thaliana*¹⁴ and some researchers have looked to other plants – C4 and CAM photosynthesis – as potential sources of improved photosynthetic architecture for C3 plants, such as through the C4 Rice Project¹⁵.

The introduction of a ‘CO₂ concentration mechanism’ (CCM) is the second pathway. A CCM has been proposed for C3 plants to provide more CO₂ relative to O₂ in the vicinity of RuBisCO to reduce oxygenase activity¹⁶. This mechanism is derived from bacteria and green alga such as *Chlamydomonas reinhardtii*, which photosynthesise in low-carbon aquatic environments and have as such developed methods for concentrating carbon near RuBisCO; C3 plants lack any such mechanism. A number of algal genes code for carbonic anhydrases, enzymes involved in the bidirectional conversion of CO₂ and H₂O into bicarbonate – by incorporating this assembly of genes into plants, biologists intend to provide C3 crops with their own CCM.

A third pathway to improve photosynthesis is the modification of photoprotection, whereby plants dissipate excess light energy to protect themselves from too much sunlight. By reducing the time it takes for the plant to respond to changes in light conditions researchers have been able to increase seed yield in soybean by as much as 33% in field trials¹⁷. Work is ongoing to incorporate this and other strategies into potato and rice through the PhotoBoost project (see below), which stacks a number of these pathways in order to boost photosynthetic potential.

The fastest and most transformative options for improving photosynthesis rely on crop biotechnology^{8,18}. Different generations of crop biotechnology are subject to different forms of regulation – and popular acceptance – in different parts of the world¹⁹. There has been significant debate in many countries over how to regulate site-directed nuclease technologies that introduce no ‘foreign’ DNA into target organisms^{20–22}. These debates have often centered on the perceived benefits and risks of biotechnology amongst different groups²³, particularly in light of the public backlash against first-generation genetically modified organisms (GMOs) in Europe. Some researchers have suggested that, for biotechnology crops to have impact, someone needs to plant them²⁴. There is, as such, a parallel need to understand whether there is interest amongst stakeholders involved in food production for the abiotic stress resilience that modern biotechnology can deliver and how that interest might vary between countries with different farming contexts and biotechnology regulation. Here we outline our stakeholder-led approach to this problem, using the RRI framework as a starting point.

Photoboost and responsible research and innovation in the horizon 2020 programme

The PhotoBoost project is funded by the European Commission and aims to improve photosynthetic performance of rice and potato by 20–25% leading to an expected 25–30% increase in plant biomass. Led by Fraunhofer IME in Germany, the project also involves a dedicated social science work package to explore the potential impacts of improved crops on society, economy and environment; this emphasises engagement with the potential users of PhotoBoost technology, who we consider to be stakeholders involved in food production on farm, processing, breeding or research.

Engaging farmers with science is not new—it was formalised in the post-war period through national extension services that provided farmers with evidence-based advice—but its purpose and form and has changed over time in line with evolving views on how (and if) agriculture should be supported in achieving specific economic or social outcomes. The privatisation and rollback of extension services in many countries, in step with other forms of economic liberalisation from the 1980s onwards, led to the development of a heterogenous, demand-driven system for agricultural knowledge^{25,26}. Private sector research, independent agronomists, university research institutions, levy organisations, non-governmental organisations, producer associations and supermarket groups have become key players in the agricultural landscape, each with their own relationship to formal science, farmers and to biotechnology²⁷. The growth of the heterogenous, demand-driven knowledge system coincided with challenges to the dominant “linear” model of innovation that saw farmers as passive adopters of agricultural technology and, from those challenges, new ways of thinking about agricultural innovation²⁸.

In parallel, there have been calls to engage the wider public in science and in recent years it has become formalised to a greater extent through the RRI, which was embedded in European Horizon 2020 calls²⁹. RRI emerged, in part, from the debate in Europe about genetically modified crops (GMOs) and is premised by the concept that societal expectations are essential elements underlying the potential sustainability of technological innovations. The need to engage a wide range of societal actors in the development of science and technology is at the core of RRI³⁰. RRI also emphasises anticipation, responsiveness and institutional reflexivity, that is, the ability for researchers and innovators to anticipate and respond to the needs, values and expectations of society as they evolve and as new knowledge emerges³⁰.

The slow adoption of Green Revolution crops in Sub-Saharan Africa spurred Chambers, Pacey and Thrupp to challenge agricultural science to better address the needs of farmers in suboptimal conditions in the 1980s³¹. Their work anticipated RRI’s later focus on aligning scientific research with societal needs; it was not the failure of farmers working in sub-optimal conditions to appreciate the value of Green Revolution inputs, it was agricultural science that had failed to take their needs into account when developing new varieties or test them in conditions closer to those found in Sub-Saharan Africa. When compared with ‘classical’ models of innovation, responsible innovation emphasises some kind of stakeholder engagement at an early stage. It likewise challenges

the assumptions that innovation is purely technological, should be viewed primarily through an economic lens or is inherently good³². Baum et al.³³ point to the disconnect between the priorities and techno-optimism of scientists compared to other groups, also manifested in technology evaluations that do not reflect differences in opinion about what matters most (i.e. not only environmental risk in the case of biotechnology crops but factors such as corporate control and other socio-economic concerns)^{23,34}.

The European Union's support for projects that focus on boosting photosynthesis requires fresh approaches that embed the principles of responsible innovation whilst acknowledging the history of farmer engagement in the agricultural sciences more widely. Our approach to implementing the RRI framework as we engaged farmers and other stakeholders is outlined in Table 1.

The research questions we set out to answer were:

- What do farmers and other agrifood stakeholders think of boosting photosynthesis as a crop improvement aim?
- How do they view the use of crop biotechnology to achieve it?
- How do they think such crops should be regulated?

Given claims made about the potential for biotechnology crops to benefit farmers in the Global South³⁶ and calls for their involvement in biotechnology research^{37,38}, we also aimed to include several low- and middle-income (LMIC) countries in the study alongside our focus on European countries.

Results

In total seven focus groups were conducted across four countries, six in person and one online (see Fig. 1). The focus groups involved 62 people, 20 in the United Kingdom (m = 17, f = 3), 14 in the Philippines (m = 8, f = 6), 20 in Bangladesh (m = 10, f = 10) and eight in Spain (m = 6, f = 2). The discussions lasted between 40 and 90 min. Below we describe each country in which we conducted focus groups and explain more about relevant crop types and biotechnology development to date.

United Kingdom

The UK ranks 7th in European potato production and is a key seed potato exporter, particularly from Scotland's east coast where potato covers 28,000 hectares. We spoke with growers, seed breeders and agronomists at a Perth and Kinross conference and with potato researchers, processors and packers in England via online meeting.

Since leaving the EU in 2020, the UK Government has pursued greater biotechnology leniency, passing the Genetic Technology (Precision Breeding) Act in 2023, meaning gene-edited plants and animals will not be regulated the same way as first-generation GMOs. No biotechnology crops are yet commercialized in the UK, although several high-profile projects have reached field trials, including omega-3-rich Brassicaceae that could reduce cardiovascular disease risk and circumvent fishing potentially depleted fish stocks³⁹.

Philippines

The Philippines produces ~ 20 million tonnes of unmilled rice annually (2022), ranking among the world's top ten producers. Home to the International Rice Research Institute (IRRI), which helped organise our focus groups, the country has been central to Golden Rice development over 20 years. Golden Rice was recently approved for commercial sale, with 140 transgenic events approved for commercial planting or consumption, including various Bt maize strains. During our visit, before commercial release, Golden Rice seed was government-provided then repurchased from growers for national distribution.

We spoke to farmers and agronomists in Nueva Ecija, central Luzon's "rice bowl"²⁴ and with researchers and regulators at Los Baños, Laguna, where IRRI is headquartered.

Bangladesh

Bangladesh is the world's seventh largest potato producer with ~ 11 million tonnes annually – potato ranks second only to rice in gross tonnage⁴⁰. It's a winter crop planted November-March during cooler weather, with simultaneous tuberisation and crop growth in the short season.

RRI element	Our approach
Anticipation aims at a more detailed understanding of the complex and multifaceted nature of the world in which emerging innovations should find a place	Through farmer engagement we explored the context into which new varieties could be launched
Inclusion requires engagement with a broad diversity of actors from these worlds	Included a range of stakeholders across four countries and two continents (two for potato and two for rice)
Reflexivity demands the actors engaged critically examine the needs, interests, issues and values at stake in processes of innovation. We invited the actors involved to reflect on different system conditions for potato breeding, cultivation and marketing and how these conditions and the emergence of hybrid potato breeding may interact	We explored these factors with the farmers and other stakeholders who we engaged, focussing on their needs, values and expectations of improved varieties (see Focus Group Protocol)
Responsiveness implies a willingness to sincerely take into account societal purposes, contexts, tensions, needs and values in shaping innovation. In this context, we invited actors to address the conditions and policies needed for a future in which hybrid potato breeding can effectively serve food security and other relevant SDGs	We addressed the future of biotechnology policy with participants and will incorporate their views into a policy roadmap for the EU Commission. We also share with participants in diverse settings the latest in photosynthesis research and likewise involve PhotoBoost plant scientists in discussions around the findings of our qualitative research in order to identify potential opportunities for the biological science to respond to the stated needs of end users

Table 1. Elements of RRI and our approach to them (adapted from Stermerding et al.³⁵).

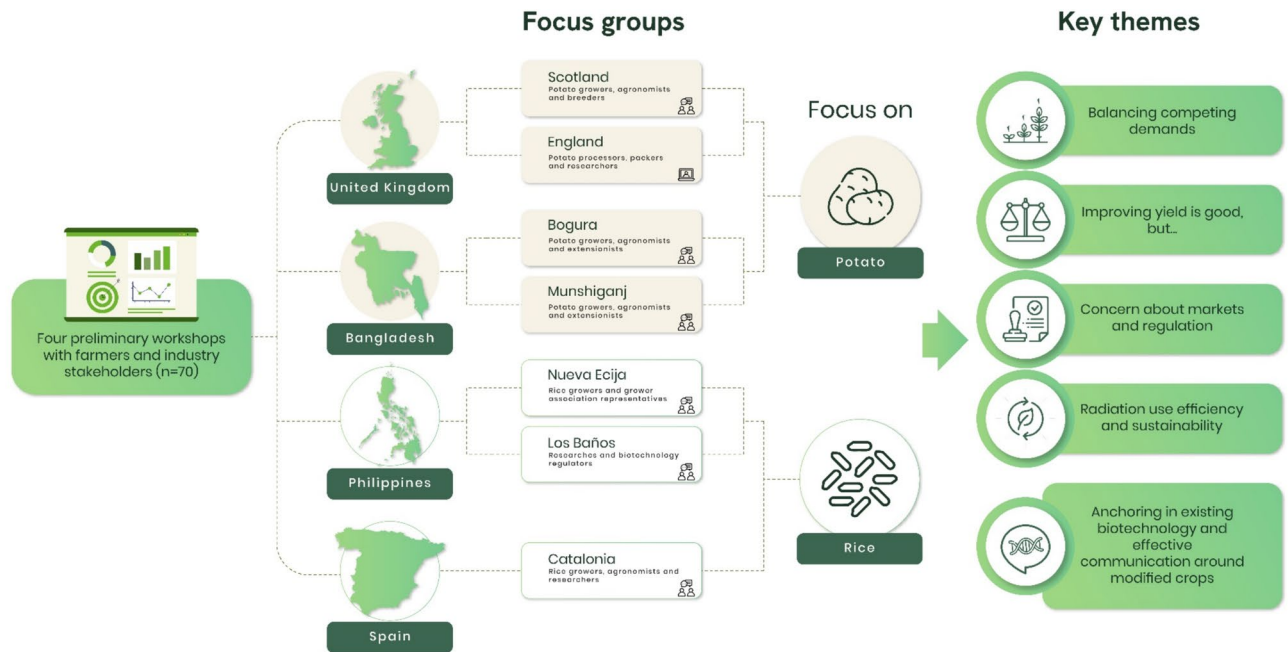


Fig. 1. Outline of the research process with locations and descriptions of focus groups, as well as main qualitative themes identified. An idea of the roles of participants is given, though it should be noted that many people have in the past or continue to act in multiple roles in the farming community (e.g. growers who are also association representatives).

Though cited as key for Bangladeshi development, lack of high-yielding varieties impedes agricultural improvement⁴⁰. Most areas suit potato production, with leading regions including Rangpur in the north, the area around Bogura in Rajshahi Division in the west and south of Dhaka near Munshiganj between the Padma and Meghna rivers.

Bangladesh first approved commercial Bt Brinjal (eggplant), late blight-resistant potato, with Bt Cotton likely following⁴¹. IRRRI's Golden Rice programme developed a strain using the popular BRRI dhan29 variety as parent line. We partnered with the International Potato Centre (CIP) Bangladesh office for focus group organisation.

Spain

Spain is the EU's second largest rice producer, concentrated in Andalucia, Extremadura, Catalonia and Valencia – eastern regions known for Bomba rice used in paella. Initially grown along Guadalquivir and Ebro deltas, rice now grows in drier inland areas⁴². Our farmers were based in Pals, Catalonia, near the Ter River, where canals irrigate coastal rice production. We met during a University of Lleida event, one of our PhotoBoost partners.

Spain is the EU's largest GMO crop producer. Bt Maize covers 100,000ha, primarily in Catalonia and Aragon. Though Pals is known for rice, substantial Bt Maize production occurs there, and many farmers at our PhotoBoost presentation event were maize farmers (we subsequently split groups by crop type).

Key themes

In sum, each of the countries included in our sample are major producers of their respective crops and have their own history with crop biotechnology, with a system for approvals that has (or will have) seen commercial release of such crops. Below are the key themes identified through our analysis.

Balancing competing demands

In each country and in every location, farmers, their advisors and breeders discussed the competing demands they faced when selecting varieties and how a new (PhotoBoost) variety might fit into this picture. Respondents felt that any new varieties would need to perform at least as well as current varieties across a spectrum of competing demands for themselves, which were primarily agronomic and their customers, perceived to be storage needs and consumer expectations:

“As a potato grower, managing risk is one the biggest things. I look at how risky [a new variety] is going to be for me to grow, is it going to go down with powdery scab, is going to be go down with black leg. I try and not choose the risky variety. For potato, this included careful attention to dry matter content, which determines storability.” – Scotland, potato grower

Balancing disease and pest resistance with the needs of either supermarkets or consumers was a central topic of conversation, particularly for potato, which is assessed on its characteristics for a number of different purposes

(sold fresh or frozen for chipping for example). In the Philippines, the rice planting window is determined by both access to water and pest pressure:

“The problem here is the resistance of the varieties and currently the problem is that if the flow of the irrigation is not adjusted and you’re late... surely it will be attacked by stem borer.” – Nueva Ecija, rice grower

Farmers drew a line between issues such as planting time, storage and eating quality because new varieties could upset how they currently balance these competing demands, some of which are beyond their control. This theme permeates those below.

Improving yield is good, but...

Improving yield was considered desirable by some participants, but was also contrasted by others, as a discrete breeding aim, with the importance of improving pest resistance and other desirable traits:

“I think it [improving yield] ticks every box really in that respect, that’s the beauty of it isn’t it? [A] 30% increase in yield would be, people would bite your hand off for that...” – Scotland, potato grower

“So it’s not just the yield... it’s got to continue to perform through post harvest, through storage and through processing into products. Yield is important, but it’s not the be all and end all.” – Scotland, agronomist

“Well, my first impressions are very good, especially seeing that it can lead to improved production in the case of rice, and well, it also shows that the plant can be more productive and make better use of resources.” – Catalonia, agronomist

“No, what we need is disease resistance. First, I need to survive. Then the rest comes.” – Bogura, potato grower

Arguments in favour of improving yield tended to rest on improving efficiency, the ability to spare land for other purposes or increased profit for farmers – a caveat being that yield improvement without maintaining existing levels of varietal pest resistance could be wasted yield improvement. The discussion raised questions about whether improved yield would come from increased grain/tuber size, or a *higher number* of grain or tubers for rice and potatoes respectively. This likewise resulted in debate about which was preferable, the answer being: it depends on the market for the crop (see below).

Concerns about markets and regulation

The markets to which farmers sell their produce and in which agricultural science must operate were a key topic of discussion. Although there was relatively little concern among our Asian farming participants about consumer acceptance of modified food from growers, those involved in research and regulation were more interested in this issue, reflecting the concerns of those closer to consumers in Europe, like processors and packers in the UK. Some represented global brands and, as such, any proposed benefits of new varieties would have to outweigh the risk of adopting biotechnology crops in any part of the world:

“It’s that commercial acceptance for us involved in global companies, what we do here will impact our customer base in Argentina... in Australia and wherever. And it’s when that trade off - that the advantages of being involved and potentially seeing some benefits of crops with this technology outweigh the negative impacts of the commercial side of things...” – England, potato processor

Other participants also reinforced the idea that benefits lead to greater public acceptance of biotechnology crops:

“So regardless of whether it’s GM or not, as long as they realise the benefit of having it, taking it, they [the public] will really accept it, that’s what I learned personally from our experience.” – Los Baños, researcher

Likewise, the protocols in place to ensure the safety of biotechnology crops in LMIC countries where commercialisation was possible is considered a source of improved acceptance:

“In the Philippines we are having a rigorous safety risk assessment concerning the safety of the GM crops for human and animal consumption, and environment as well, that’s why we have five different agencies that are involved in the regulatory policy. And what we do in the biotechnology office... is that we also cater and do public briefing for regulations that are in place, so that we can assure them that these technologies... have already gone through the rigorous risk assessment process.” – Los Baños, regulatory representative

The exception here is Golden Rice, which in both Philippines and Bangladesh has struggled for regulatory approval, to the voiced annoyance of some biotechnology researchers in the Philippines, who noted that “European-funded” groups had stood against its development and commercialisation, as well as that of locally-developed biotechnology crops, such as Bt Eggplant. Farmers’ concerns with respect to markets link to the earlier theme of balancing competing demands with respect to agronomy and what their customers demand:

“And the cooks, “els cuiners”, the chefs, they have to cook it, they have to try it, they have to... the big difference with the rice between the rest of the world and Spain is that we do rice, round rice, and that’s just for the cuisine...” – Catalonia, rice grower

When it comes to regulation, attitudes amongst farmers was mixed: in Munshiganj, farmers were not particularly familiar with the country’s biotechnology regulations as exemplified by this exchange:

“This is about genetically modified crops. Just like a technology has been added to brinjal, if we do the same for potatoes, would there be any issues law-wise? Does anyone know about any such laws?” – Agronomist

“No, no. We do not.” – Farmer #1

“We do not have any idea about this.” – Farmer #2

In the Philippines, farmers based their discussion around biotechnology regulation with respect to Golden Rice as opposed to the for-now more abstract notion of PhotoBoost varieties (see below). In the UK, which has no commercially-grown modified crops at the present time, participants believed that supermarkets mediated the introduction of new varieties for consumers and held most power when it came to choices around agricultural sustainability; in Catalonia, participants noted that multinational companies that develop biotechnology crops were based outside Europe due to “political constraints” to their commercialisation.

This is a very complex issue because this technology is now in the hands of multinationals. This is why it's all gone outside of Europe. And then there is a political constraint that restricts us, and this can play a role, it's difficult. – Catalonia, rice grower

A potato farmer in Scotland expressed unease at the notion of transgenes in crops, citing the example of cyanobacterial genes that decrease photorespiration. There was more focus on gene editing as a closer-to-reality biotechnological tool for breeders in the UK than any techniques that might involve transgenesis and the longer route to regulatory approval for any such crops.

Radiation use efficiency and sustainability

An emergent theme that participants dwelt on is radiation use efficiency, where the prerogative to use sunlight optimally was discussed in different contexts and tied to sustainability. Growers in Scotland for example, highlighted the need for them to make the most of the summer months and what is a short growing season – in Bangladesh, though, potato is a winter season crop, squeezed between the onset of cooler weather and warmer rice-growing season, where farmers favouring quick-maturing varieties of 60–70 days. In this respect tropical agriculture faces particular demands, as farmers are not only taking into account the needs of one crop but several over the course of a year and have to consider *total* on-farm yield of multiple crops:

“... for us, one harvest is closely tied with another harvest. If we can harvest potatoes within a short time... if it is 90 days or 85 days, we cannot plant the BRRI (Bangladesh Rice Research Institute) rice earlier. If I can plant the BRRI rice, we will get more yield. That's why we want a variety that is in keeping with the needs of the time. A variety, that will allow us to grow potatoes easily and also start growing the next crops earlier, which too will give us more yield.” – Munshiganj, potato grower

As such, photosynthetically-improved varieties that mature faster could offset some of the risk of such narrow planting windows (*ceteris paribus*). Better photosynthesis was also linked to sustainability, as maximising the free and clean energy of sunlight to improve yield was preferable to mining, processing and applying agricultural inputs to their crop:

“... we've got a free and infinite resource in terms of sunshine, so we should be maximising the energy that we capture from there, we shouldn't be extracting oil to make nitrogen when we've got free sunshine.” Scotland, potato breeder

Anchoring in existing biotechnology and effective communication around modified crops

In those countries where biotechnology crops had already been commercialised or grown, participants anchored their understand of new varieties and the issues they might bring in those existing crops – in Nueva Ecija, this was Golden Rice, which some of the farmers had grown through government programmes and, in Bangladesh, Bt Brinjal:

“We already planted [Golden Rice] last year but all harvested rice were given to PhilRice, nothing left to us. We are not allowed to eat [it].” – Nueva Ecija, rice grower

In the case of Bt Brinjal, Bangladeshi farmers and advisors noted that there had initially been a false perception Bt Brinjal was resistant to *more than* stem borer and had as such not sprayed adequately for other pests. An advisor suggested the small size of the fruit was smaller than common varieties and had not been accepted by farmers (though it should be noted that both higher yields and greater revenue have been reported for Bt Brinjal, which is grown on more and more land each year⁴³). It was in light of these issues farmers and advisors discussed the need for more information around modified crops, not only for themselves but with a view to explain their decisions to others:

“If it's up to me... then we do not understand it thoroughly yet. We need more information and knowledge so we can also further explain it to the people.” – Nueva Ecija, rice grower

Given the lack of commercialised biotechnology crops in the UK, there was no evidence of anchoring and more trepidation about transgenic crops.

Discussion

It is important to understand how the plant breeding aims of biotechnology research projects funded by the EU are perceived by farmers and those involved in food production; without these considerations, any potential impacts of what is often promoted as a tool for more sustainable agriculture could be muted. The RRI framework emphasises the importance of involving such actors in the development of new technology and the focus groups

we conducted provide a window into Here we explore the findings in context and suggest how future European research funding can better respond to issues we have identified.

Across each country, both for rice and potato, we found that a consistent need for farmers is the performance of any new variety through the supply chain – agronomic, processing and market performance must be at least as good as existing varieties and with clear benefits that outweigh the perceived risk of biotechnology, which varies by location.

The focus groups also indicated that participants expected the impacts of PhotoBoost crops to resemble more those of first-generation biotechnology crops, like Bt Maize, than second-generation Golden Rice. Some researchers have argued that understanding farmer demand for Golden Rice is key²⁴ and, for others, its demand amongst consumers⁴⁴. The direct benefits of PhotoBoost crops will be seen to accrue for farmers rather than consumers (an issue faced by first-generation biotechnology crops whether true or not⁴⁵) with their sale and distribution dictated by the market; this is in contrast to Golden Rice, the supply of which is controlled, when grown at all, by the Philippine government. Despite Golden Rice being effectively blocked in both the Philippines and Bangladesh, other biotechnology crops have been approved during its 20-year development, suggesting PhotoBoost varieties are most likely to benefit LMICs with favourable biotechnology regimes in place – the political economy of seed choice is thus rather different than in Europe where GMO commercialisation is a challenge. We found that perceptions of biotechnology varied by location, owing in part to the starkly different regulatory regimes in place and due to farmer knowledge about biotechnology regulation. These differences could indicate that acceptance of technology, something often ill-defined but frequently invoked in discussions around biotechnology^{33,46}, can be influenced by regulation, rather than biotechnology acceptance determining regulation⁴⁷. Likewise, farmer familiarity with Golden Rice in the Philippines, for example, illustrates how prior experience with biotechnology crops can influence their openness to plant breeding innovation.

The “mission” in photosynthesis research is often cast as improving yield in the context of an ever-growing human population^{5,18,48}. Crop biotechnology is also promoted for this reason⁴⁹. We found that some participants questioned the ongoing importance of yield in favour of other traits. This finding is reflected in previous research that identified a similar trend amongst agrifood stakeholders across the EU⁵⁰, but our research demonstrates the reasoning behind this for some participants: farmers focus on avoiding losses to pests rather than boosting yield, reflecting productivity concerns rather than sustainability *per se*. However, the better use of “free and infinite” sunlight was also valued by some participants as a means to more sustainable crop production, as genetic improvements could boost nitrogen use efficiency and reduce the application of synthetic fertilizer^{48,51}. This bridges the distinction between traits for yield and traits for sustainability.

Our research demonstrates the value of embedding RRI principles in EU research funding from project inception rather than as an add-on evaluation. Future research funding in this area could be made contingent on proposals contending with theories of change in agriculture: how would improving yield in a particular crop meet the challenge of a growing population, given constraints elsewhere in the food system and the farmer focus on biotic stresses? Theory of change refers to the process of describing the steps needed to achieve a particular aim and pinpointing weaknesses or gaps in current approaches. Some researchers have called for complexity-aware theories of change to be used in agricultural innovation systems where heterogenous actors continuously adapt their strategies and actions in response to changing conditions and what other actors do⁵². Understanding the complexity of agricultural systems, from agronomy through to market demand, is a prerequisite for realising impact within them and may also necessitate a deeper level of stakeholder engagement than other approaches.

At the same time, balancing more applied concerns with the blue skies research that has enabled us to make long strides in boosting crop photosynthesis is also important, but presents a challenge for RRI – how to weigh worsening but longer-term abiotic stresses, perceived by scientists as most important, against nearer-term biotic stress that most concerns farmers?

Limitations

There were several limitations to our approach. One is the reliance on focus groups, which, whilst providing researchers with insight into salient issues for specific groups of people, can also suffer from biases introduced by participants trying to appear favourable to others⁵³. Focus groups can also be intimidating for people who are shy or consider themselves inarticulate⁵³.

Another is the potential bias introduced by handing over some control over recruitment to outside organisations – more well-connected, technologically-open farmers may have therefore been included in our sample, which is a challenge to overcome in agricultural social science. Ensuring a gender balance was also difficult in certain regions where professional farming tends to be male dominated.

Future research in this area could employ mixed-methods approaches to reduce the limitations of a single method and female-only focus groups may offer a means of ensuring that the effects of gender, a key factor for RRI research, are given fair consideration. A focus on more biotechnology-forward countries in North and South America could provide further insight into the potential of photosynthesis boosting research.

Methodology

We took an applied qualitative approach to this study, which relied on focus group discussions to generate data; we follow the COREQ⁵⁴ qualitative analysis reporting criteria to explain our methodology. Ethical approval for the study was granted through the University of Oxford Social Sciences & Humanities Interdivisional Research Ethics Committee (REF: R77406/RE001). Our methods were carried out in accordance with relevant guidelines and regulations. We obtained informed consent from all participants prior to data collection.

Focus groups help generate new ideas, the assessment of potential ideas and insights into the differences in opinion that exist between members of particular groups^{55,56}, in this case between countries, continents and

crop types. In our focus group discussions we aimed to understand stakeholder attitudes towards the aim of improving photosynthesis, the use of biotechnology to improve it and challenges it helps address.

Initial farmer workshops with potato growers and industry at an event at the University of Cambridge in 2022 allowed us to introduce the PhotoBoost project and pilot our questions with 70 participants.

Our sampling framework was primarily purposive, but with some elements of convenience sampling due to existing relationships with organisations capable of helping us facilitate focus groups outside the United Kingdom. We designed our sampling framework with breadth in mind, to provide perspectives on modifications to rice and potatoes from low- and middle-income countries and compare these to two European countries, which, due to the source of our funding, were central to this project. We also sought to understand potential regional differences within countries to minimise the effect of geography on responses, aiming for two focus groups in different areas of each country. We required these countries to be: (1) significant producers of rice or potatoes and (2) host organisations that could facilitate these focus groups by helping with recruitment, coordination and interpretation of results.

We sought focus group participants from organisations involved in potato or rice production at farm level, in the value chain for those crops or working on their improvement through plant breeding, with an emphasis on farmers and their advisors. Recruitment of individuals to focus groups was envisioned as being handled primarily by host organisations (discussed further in the Limitations section); we set requirements for participants, such as a gender balance where possible, as well as a diversity of farm size.

The host organisations were asked to provide peer interviewers, often researchers or project assistants, who had previous experience with focus group discussion convening or were trained by Jonathan Menary (male, researcher, *PhD*). Participants were contacted by partner organisations through a variety of methods: in the UK this was done primarily by email, but in the Philippines and Bangladesh most participants were contacted by phone. In Catalonia, participants were recruited through a local rice grower group and posters for the talks taking place either side of the focus group discussions were displayed in shops.

We intended to conduct focus groups in person, but remained open to online discussions where this was more convenient for attendees as previous work has shown both approaches to be comparable⁵⁷.

In each case the focus group discussions followed a brief presentation by Jonathan Menary, who introduced the project aims, methods and outputs. In cases where English was not the native language, the presentation was translated verbally slide-by-slide by a peer interviewer from host organisations (although it should be noted, many participants could speak or understand written English, if not wholly then to some extent). In Catalonia the presentation was presented by a Catalan-speaking colleague from PhotoBoost and slides were translated into Catalan, the dominant language of the region. Participants were therefore aware of the intentions of the researcher regarding their involvement.

Although we were conscious that un-critical presentation of the project could introduce bias, it was decided that some knowledge of PhotoBoost plant breeding aims and processes would be crucial to the group discussion; we asked our colleagues in-country to scrutinise the presentation before the group discussions and make any necessary changes to reflect local knowledge and communication styles. Participants were then invited to sit around a table or in a circle and introduce themselves. After the introduction, Jonathan Menary began asking questions as per our Topic Guide, which were translated for the group by the peer interviewer. The peer interviewer summarised the discussion for Jonathan Menary as the discussion progressed. The discussions were audio recorded via Dictaphone. Jonathan Menary had no prior relationship with any of the participants but one who had been interviewed as part of a previous project. Peer interviewers had had interactions with some participants through their roles in previous projects.

Audio recordings were transcribed by third-party companies, then cleaned by Jonathan Menary, who with Sebastian Fuller carried out a thematic analysis in sequential order, coded inductively by country, using *NVivo*; the themes were then compared country by country. Partners in non-English speaking countries helped validate translation and meetings were held to sense check our thematic analyses.

Data availability

The datasets generated and analysed during the current study are available in the Oxford University Research Archive repository [<https://doi.org/10.5287/ora-a4zq6nx28>].

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Author contributions

Jonathan Menary conceived the research design and analysis, collected the data, performed the analysis and wrote the paper. Teresa Capell collected the data and reviewed the manuscript. Ebna Habib Md Shofur Rahman collected the data and reviewed the manuscript. Sherry Lou S. Hechanova collected the data and reviewed the manuscript. Alvin G. Tallada collected the data and reviewed the manuscript. Sebastian S. Fuller conceived the research design and analysis, performed the analysis and wrote the paper.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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