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Socioeconomic Impact of Genome Editing on Agricultural Value Chains: The Case of Fungal-Resistant and Coeliac-Safe Wheat

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Abstract: Genome editing (GE) is gaining increasing importance in plant breeding, since it provides opportunities to develop improved crops with high precision and speed. However, little is known about the socioeconomic impact of genome editing on agricultural value chains. This qualitative study analyzes how genome-edited crops could affect agriculture value chains. Based on the hypothetical case of producing and processing fungal-resistant and coeliac-safe wheat in Germany, we conducted semi-structured, in-depth interviews with associations and companies operating in the value chains of wheat. A value chain analysis and qualitative content analysis were combined to assess the costs and benefits of the crops studied along the value chains of wheat. The results show that the use of fungal-resistant and coeliac-safe wheat can provide benefits at each step of the value chains. Fungal-resistant wheat benefits actors by reducing the problems and costs resulting from fungal-diseases and mycotoxins. Coeliac-safe wheat benefits actors by producing high value-added products, which can be safely consumed by patients suffering from coeliac disease. However, the results also show that low acceptance of GE by society and food retailers poses a significant barrier for the use of genome-edited crops in agricultural value chains.

Keywords: plant breeding; genome editing; value chain analysis; socioeconomic impact; costs; benefits; wheat; fungal diseases; coeliac disease; mycotoxins

1. Introduction

Securing the food supply of the world´s increasing population is an urgent challenge for agriculture production [1]. By 2050, the global population is expected to increase to 9.7 billion [2]. The Food and Agricultural Organization of the United Nations (FAO) predicts that compared to 2005/2007, about 60% more food will be needed by 2050 with significant implications for farmers and food production systems [3]. At the same time, agriculture is affected by limited availability of natural resources (e.g., water and land), climate change, pests and diseases, biodiversity loss, as well as increasing societal demands for more socially, economically, and environmentally sustainable production methods. One strategy that may contribute to meeting the challenges is the development of improved crops by genome editing (GE) [4].

GE is a general term for a set of advanced molecular breeding techniques, which can be used for targeted modification of DNA sequences in crops, animals, and humans [5]. Unlike conventional breeding techniques and classical genetic engineering, which draw upon casual mutations of many genes respectively via the random insertion of new genes, GE "allows the selective mutation of one or a few genes exclusively and the precise modification or replacement of entire genes, whether from closely or distantly related organisms" [6] (p. 25). The origin of the technology dates back to the 1970s and 1980s when first targeted genomic changes were produced in yeast and mice [7]. Since then, a variety of genome editing techniques has been developed. Existing GE techniques can be divided into three approaches: (1) *Site-directed nucleases (SDN*), including *Meganucleases (MN*), *zinc-finger nucleases (ZFNs*), *transcription activator-like effector nucleases (TALENs*), and *clustered regularly interspaced short palindromic repeats/ (CRISPR/Cas*); (2) *oligonucleotide-directed mutagenesis (ODM*), and (3) *base editing (BE*) [8]. Of these techniques, the CRISPR-systems and TALENs are most frequently used for genomic alterations in crops [9]. A detailed description of GE techniques is provided by the studies of Kamburova et al. [10] and Modrzejewski et al. [8]. A comparison of GE with techniques of conventional breeding (e.g., mutation breeding by radiation) and classical genetic engineering can be found in Bujnicki et al. [6].

Several authors highlight the potential of GE for improving crops and securing the world´s food supply [4,11,12]. The main advantage of GE techniques over previous mutation breeding techniques and classical genetic engineering is the possibility to modify crops with higher precision and speed [8,11,13]. Furthermore, experts agree that GE offers more opportunity than conventional breeding techniques to produce crops with higher agronomic performance (e.g., disease resistance, drought tolerance, increased yields), product quality (e.g., enhanced nutritional value, storability, removed allergens), and climate change resilience [11,14,15]. Concerns about GE in crops include the potential occurrence of unintended cleavage and mutations at untargeted genome sites [8]. Although off-target effects occur less frequently in applications of GE compared to conventional mutagenesis techniques [8], they may challenge breeders since they can trigger genomic instability, cytotoxicity, and cell death [16–19].

In the last decade, GE techniques have been increasingly used in a multitude of crop species to investigate gene functions and improve traits [8,20]. In some countries like the United States and Canada, genome-edited crops have already been placed on the market [21] or are close to market launch [22–26]. By contrast, in Europe genome-edited crops are far from being commercialized. One barrier for the use of genome-edited crops in Europe is the strict regulation of crops derived from GE [27].

After several years of uncertainty about the regulation of GE, the European Court of Justice (ECJ) ruled on 25 July 2018 (Case C-528/16) that "organisms obtained by mutagenesis are GMO" [28] (p. 1) and thus fall within the scope of Directive 2001/18/EC, including all legal obligations resulting from this Directive. Only those mutagenesis techniques that have a long safety record are exempt from this regulation. Since this is not the case for GE, agricultural products obtained by targeted mutagenesis from GE are genetically modified organisms (GMO) [28]. The European GMO regulatory framework imposes high requirements for the commercialization of GMO including a complex and extensive authorization procedure where the safety of the product is assessed before deliberate release and placing on the market. Deliberate release of GMO into the environment is addressed in Directive 2001/18/EC, which prescribes a detailed approval procedure and the obligation to establish a public register. Furthermore, the Directive sets requirements for product labeling. Additionally, Regulations EC No. 1829/2003 and 1830/2003 deal with genetically modified food and feed and the traceability and labeling of GMO and thus set the legal framework for placing GMO products on the market. Several studies show that the regulatory framework in Europe can be a source of additional costs along the agricultural value chain of GMO [29]. These costs can be divided into costs of ex-ante regulation and costs of ex-post liability [30,31]. At the farm level, costs of ex-ante regulation can be specified as administration and publication costs for handling the requirements arising from Directive 2001/18/EC. Farmers must also take into account damage prevention and coexistence-measure costs, such as isolation distances, buffer zones, or time isolation. Costs of ex-post liability comprise damage and liability costs, which mainly depend on price differences of different products such as organic, conventional, or GMO produce, the quantity of products affected, and the labeling threshold [32]. Other costs include the costs for establishing separate production chains in order to guarantee segregation and identity preservation along value chains [33].

When it comes to GE crops under the European GMO regulatory framework, further challenges for the agricultural value chain have to be taken into account. GMO can be identified as such by a multitude of detection methods [34], which target characteristic elements in the genome. However, these techniques are not applicable to GE products, which do not necessarily contain foreign DNA and where changes in the genome may not be distinguished from naturally occurring mutations. For those cases—especially when it comes to heterogeneous samples such as agricultural commodities—prerequisites for detection and identification are commonly not given [35]. Like GMO, genome-edited products need market approval under the European regulatory framework and have to comply with the existing labeling threshold of 0.9%. For non-approved GMO, a zero-tolerance policy is applied in the EU, which means that these products must not be traded. This conflicts with the regulatory setting of most other major trading partners for agricultural commodities outside the EU [36]. Regardless of the high barriers for commercial applications of GE in Europe, there is great interest in understanding the potential socioeconomic impact of GE on the agribusiness.

The body of literature on the socioeconomic aspects of GE in crops is limited and mainly composed of review and opinion papers about the societal opportunities and challenges of GE [4,12,14,37–39]. Some authors discussed legal [40–42] and ethical issues [43–45], while others focused on evaluating the social acceptance of GE in crops [46–48]. Whelan and Lema [49] proposed a research program for the socioeconomic impacts of GE regulation. However, no empirical study of socioeconomic aspects of GE has been conducted yet. Consequently, the current knowledge about the potential socioeconomic impact of GE on agricultural value chains is insufficient. In particular, there is a lack of knowledge about the requirements and actors' motives to produce and use genome-edited crops. Furthermore, little is known about the potential costs and benefits, the economic risks, the drivers and barriers, and the challenges for using genome-edited crops in agricultural value chains.

The present study seeks to contribute to filling the gaps by exploring ex-ante the socioeconomic impact of GE in crops. Based on a hypothetical case of producing and processing genome-edited crops in Germany, we aim to analyze empirically how GE could affect agricultural value chains. In particular, the study will answer the following research questions:

(1) What are the requirements for using genome-edited crops in agricultural value chains?
(2) What are the motives of actors in agricultural value chains to use genome-edited crops?
(3) What are the costs and benefits of using genome-edited crops in agricultural value chains?
(4) What are the economic risks of using genome-edited crops?
(5) What are the potential drivers and barriers for using genome-edited crops?
(6) What are the challenges for the use of genome-edited crops?

We assume that by better understanding the impact of GE on agricultural value chains, we can contribute to the discussion on the socioeconomic consequences of GE in crops.

2. Conceptual Framing

The conceptual framing used for analyzing the socioeconomic impact of GE on agricultural value chains draws on the value chain concept [50]. The value chain concept was first popularized by Porter [51] and has been increasingly used as a framework for studying innovations in agricultural value chains [52–54]. Value chains describe "the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use" [50] (p. 4). Activities in agricultural value chains involve the provision of input services (e.g., plant breeding, production of seed), the cultivation of crops, and the processing of crops into food, feed, and industrial products. Furthermore, the activities include storage, transportation, and marketing of agricultural products.

In this study, we conceptualize GE as an innovation that affects agricultural value chains by providing new varieties with improved characteristics. We assume that the production and use of genome-edited crops lead to changes that have implications for the economy, the society, and the environment. Such effects are often summarized under the term "socioeconomic impact". However, there is no clear understanding of what is included in the term 'socioeconomic' in agricultural research in general. Mann [55] provides a general overview of socioeconomics in agriculture and mainly draws upon a definition from Boyer [56] (p. 744) who suggests that "socio-economics is about the investigation of the origin, transformation and impact of governance structures in modern societies". According to Mann [55] (p. 3), "socioeconomics should focus on the institutional arrangements people have given themselves to organize social, economic and political relations". Referring to GMOs, Catacora et al. [57] state that there is no agreed definition of the term "Socioeconomic impacts (SEI)" but that it includes different social and economic factors. In this study, we define the socioeconomic impact of GE as possible changes, resulting from the use of genome-edited crops along agricultural value chains compared to conventional crops, which affect the actors involved, the environment, and society as a whole. Positive changes may include quality improvements, yield increase, or cost savings in the production and processing of crops. Negative changes may include additional costs of production or economic risks, such as liability issues.

3. Materials and Methods

We have chosen a qualitative research approach based on case study and scenario methods [58,59] for analyzing the impact of GE on agricultural value chains. The case study selected for the analysis are the value chains of wheat. Wheat is one of the most grown crops in the world and a major component of the diet of humans and livestock in temperate regions [60]. In Germany, farmers harvested about 20.3 million tons of wheat grown on more than 3.0 million hectares of cropland in 2018. The area represented 49% of the total area under cereal production and 26% of the total acreage in Germany in 2018 [61]. Many different industries of the food and non-food sector use wheat or wheat-based products as input for production. Given its economic importance and diversity, the value chains of wheat provide an excellent case for in-depth studies of the impact of GE on agricultural value chains. The following section provides detailed information on the value chains of wheat, the breeding goals selected for analysis, and the methods for collecting and analyzing the data.

3.1. *The Case Study*

3.1.1. The Value Chains of Wheat

Based on information obtained from the interviews, Figure 1 shows the map of value chains involved in the production and processing of wheat and how the value chains are linked by different input and output relations.

The value chains of wheat consist of several value-added steps including crop production as well as up and downstream value-added steps. Upstream value-added steps of crop production include the development of new breeding techniques such as GE, the breeding of new wheat varieties, and the production of seed. Downstream value-added steps of crop production include the processing of wheat into several products for consumption in the food and non-food sectors. The different steps of the value chain are linked by different levels of trade including agricultural trade as well as wholesale and retail.

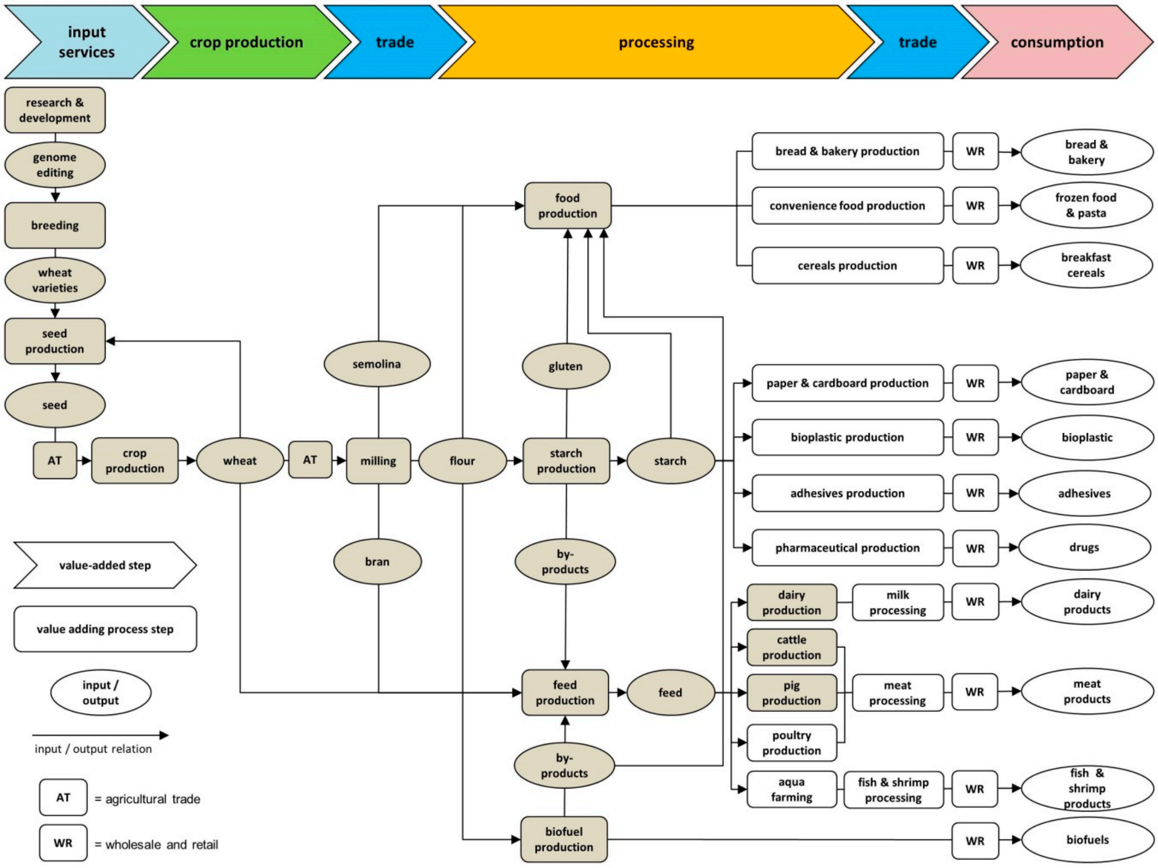

Figure 1. Map of value chains involved in the production and processing of wheat.

The processing of wheat starts in the milling industry, which uses wheat for producing different inputs for food production (e.g., flour, semolina), starch production (e.g., flour), feed production (e.g., bran), and biofuel production (e.g., flour). In food production, these inputs are used to produce food like bread and bakery, convenience food, or breakfast cereals. In starch production, these inputs are used to produce different types of starch, which are supplied to the value chains of the food and non-food sectors. The value chains of the non-food sector use starch-based products as input for producing paper and cardboard, bioplastic, adhesives, and pharmaceutical products.

Another value chain that uses wheat is the value chain of feed production. The value chain of feed production produces feed which is used in dairy production, animal breeding, cattle, pig and poultry fattening, and aqua farming. The output of dairy production, animal fattening, and aqua farming (i.e., milk, meat, fish, and shrimps) is processed into different food including dairy, meat, fish, and shrimp products. Last but not least, the value chain of biofuel production uses wheat as feedstock for producing biofuels.

Several linkages exist between the value chains of food, starch, feed, and biofuel production. The value chain of starch production is linked to the value chain of food production by supplying various starch-based products (e.g., sweeteners and thickeners) to food production. The value chain of feed production is linked to the value chains of starch production and biofuel production since it uses different by-products from the production of starch (e.g., gluten or liquid substances) and biofuels (e.g., dried distillers grains with solubles) as input for producing feed. The value chain of biofuel production is linked with the value chain of food production since by-products of biofuel production (e.g., gluten) serve as input for producing food.

3.1.2. Breeding Goals

We selected two hypothetical breeding goals, which have not yet been successfully integrated into the plant genome by conventional breeding methods or genetic engineering but which breeders may achieve with the help of GE. Both breeding goals are expected to be relevant for the value chains of wheat.

The first trait is fungal-resistant wheat. We define fungal-resistant wheat as a variety that is characterized by a multiple resistance to several fungal diseases including powdery mildew (*Blumeria graminis sp. tritici*), yellow rust (*Puccinia striiformis*), brown rust (*Puccinia triticina*), septoria leaf blotch (*Septoria tritici*), and Fusarium head blight (*Fusarium* spp.). The control of fungal diseases is one of the main challenges for crop production around the world. Fungal diseases can decrease yields and the quality of crops [62,63]. Furthermore, they can increase the costs of cultivating and processing crops due to fungicide applications and additional handling of the harvested crops (e.g., sorting, cleaning) [64,65]. Another problem related to fungal diseases is the production of mycotoxins [66,67]. In particular, the mycotoxins produced by Fusarium head blight—deoxynivalenol (DON) and zearalenone (ZEA)—pose a risk for humans and livestock since they can cause poisoning as well as fertility and growth disorders [68,69]. Cultivating and processing wheat varieties that are characterized by a resistance to Fusarium head blight and other fungal diseases may contribute to reducing these problems in the value chains of wheat.

The second trait is coeliac-safe wheat. We define coeliac-safe wheat as a wheat variety that is suitable for consumers suffering from coeliac disease. Coeliac disease is an autoimmune disease of the small intestine, which is caused by an allergic reaction to gluten, a protein found in wheat, barley, and rye. Coeliac disease is one of the main food intolerances worldwide and its prevalence is increasing [70]. Studies showed that coeliac disease affects about 1% of the population in Europe [71]. Typical symptoms of coeliac disease include gastrointestinal problems such as diarrhea, weight loss, bloating, flatulence, abdominal pain, and non-gastrointestinal abnormalities such as iron deficiency anemia, bone disease, and skin disorders [72]. Currently, the only effective treatment for coeliac disease is a life-long gluten-free diet [72,73]. However, adherence to a gluten-free diet is rather difficult since gluten is added to many food products for their viscoelastic properties [74,75]. Furthermore, gluten-free products are often less healthy and more expensive than conventional gluten-containing products [70,74,76]. Wheat varieties that do not cause coeliac disease may provide an alternative to a gluten-free diet for those who are affected.

Breeders using conventional breeding techniques face many difficulties in developing wheat varieties that are characterized by long-term resistance to fungal diseases. Moreover, conventional plant breeding has not yet been successful in developing wheat varieties that are suitable for coeliac patients. Based on the recent advances in wheat breeding with GE [77], we assume that GE can help breeders to develop wheat varieties that are characterized by multiple and long-term resistance to fungal diseases. Furthermore, we assume that GE can contribute to developing varieties that are suitable for consumers suffering from coeliac disease [75,78,79]. Both traits were selected in order to analyze the impact of GE on agricultural value chains from different point of views. Fungal-resistant wheat is an agronomic trait, which mainly aims to reduce the problems resulting from fungal diseases in the production and processing of wheat. By contrast, coeliac-safe wheat is a trait that aims to reduce the specific problems of consumers suffering from coeliac disease.

3.2. Data Collection

The data for the qualitative analysis were collected by semi-structured face-to-face interviews [80] conducted between February 2018 and February 2019. The interviews were mainly conducted with different associations representing the companies that operate in the value chains of wheat in Germany.

The associations interviewed were identified based on literature research. We selected the associations according to their importance for the industry they represent, i.e., we chose those associations representing the majority of the companies operating in a certain industry. The selected associations were contacted by telephone or email. Those who were willing to provide information were interviewed. All interviewees were experts who were selected according to their expertise and experiences in breeding, cultivating, processing, or marketing wheat and wheat-based products. In total, we interviewed 17 experts from 12 different associations. Out of these associations, three operated in breeding and seed production, three represented farmers and agricultural traders, and six belonged to the different industries involved in the processing of wheat (i.e., milling, food production, starch production, feed production, animal production). In addition to the interviews with the associations, we interviewed seven experts from four companies operating in breeding and seed production, starch production, and biofuel production. These interviews were intended to obtain additional information about the impact of using genome-edited crops on the value chain from a business point of view.

The interviews were about the general characteristics of the value chains including the participating actors, their economic activities, as well as the input and output relations between the value chains involved in the production and processing of wheat. Furthermore, the interviews addressed the requirements and the actors' motives for producing and using fungal-resistant and coeliac-safe wheat. Other topics included the potential changes in the different steps of the value chains due to GE as well as the cost and benefits resulting from the changes. Additionally, we asked about the potential drivers and barriers for producing and using genome-edited crops in the value chains of wheat.

We used semi-structured guidelines for guiding the interviews, which offers "a balance between the flexibility of an open-ended interview and the focus of a structured survey" [81]. The guidelines (Manuscript S1) included the same topics and questions for all interviews but individual questions were adjusted to the interviewees and the value-added steps they represented. The interviews lasted between 40 and 160 min and mainly took place in the offices of the interviewed associations and companies. All face-to-face interviews were digitally recorded and transcribed. Table 1 provides an overview of the interviews conducted in this study including information about the value-added step the interviewees represented, the interviewees (i.e., association or company), the date and duration of the interviews, as well as the number of experts interviewed.

Table 1. Overview of the interviews conducted with associations and companies in the value chains of wheat.

Value-Added Step	Interviewees	Date	Duration	Number of Experts Interviewed
Breeding and seed production	Association	26.02.2018	137 min	1
	Company	15.03.2018	124 min	2
	Association	23.03.2018	106 min	3
	Association	17.04.2018	130 min	1
Crop production	Association	22.02.2018	157 min	1
	Association	23.06.2018	132 min	3
Agricultural trade	Association	11.02.2019	69 min	1
Milling	Association	28.02.2018	110 min	1
Food production	Association	04.12.2018	144 min	2
Starch production	Association	28.02.2018	38 min	1
	Company	08.05.2018	156 min	1
	Company	14.05.2018	125 min	1
Feed production	Association	18.04.2018	131 min	1
Animal production	Association	26.06.2018	163 min	1
	Association	28.06.2018	115 min	1
Biofuel production	Company	29.06.2018	106 min	3

3.3. Data Analysis

3.3.1. Study Focus

The study focuses on the domestic production, processing, and marketing of wheat in Germany and neglects possible impacts of GE on the import and export of wheat and wheat-based products. The focal value-added steps considered in the analysis are (1) breeding, (2) seed production, (3) crop production, (4) agricultural trade, (5) milling, (6) food production, (7) starch production, (8) feed production, (9) animal production including cattle, pig, and dairy production, and (10) biofuel production. The value-added steps of poultry production, bread and bakery production, convenience food production, cereals production, as well as wholesale and retail were not considered in the analysis since no suitable experts were available for interviews. Furthermore, we neglected to analyze the impact of GE on the value-added steps downstream of starch production (i.e., paper and cardboard production, bioplastic production, adhesives production, pharmaceutical production) and animal production (i.e., milk and meat processing). Figure 1 indicates the value-added steps considered in the analysis in the grey boxes.

3.3.2. Scenarios

The socioeconomic impact of GE on the value chains of wheat was analyzed by comparing the production and use of wheat and wheat-based products along the focal value-added steps in two different scenarios.

The scenario *"without GE"* is the baseline scenario representing the current value chains of wheat. In this scenario, we assume that GE as a technique for developing improved wheat varieties is not available. Furthermore, we assume that the actors in the value chains of wheat use varieties that are prone to fungal diseases and that are not suitable for consumers suffering from coeliac disease.

The scenario *"with GE"* is a scenario representing the innovative value chains of wheat. In this scenario, we assume that GE helps breeders develop wheat varieties that are resistant to fungal diseases and wheat varieties that are suitable for consumers suffering from coeliac disease. Furthermore, we assume that crops developed by GE are regulated as non-genetically modified crops, i.e., they are not subjected to the rules of the European GMO legislation. The assumption about the regulation of genome-edited crops was made at the time when the ruling of the European Court of Justice was still pending. As a consequence, we neglected to analyze the impact of the European GMO legislation on the costs of using genome-edited crops.

3.3.3. Qualitative Content Analysis

The information obtained from the interviews was analyzed by a qualitative content analysis [82,83] using MAXQDA software. We started the analysis by developing a scheme of thematic categories to systematically structure the interview data. The categories were developed deductively from the main topics of the interview guidelines. The categories were: (1) Requirements; (2) motives; (3) changes and benefits; (4) additional process steps and costs; (5) economic risks; (6) drivers; (7) barriers; and (8) challenges. After this, we developed a coding manual according to which we assigned all relevant text sequences to the matching categories. The manual (Table S1) included a definition of each category, anchor examples, and specific rules for assigning text sequences to certain categories.

In the next step, we conducted a pretest. Two transcripts were coded independently by two researchers using the drafts of the coding scheme and the coding manual. The individual coding were compared and diverging coding results were reviewed and discussed. The procedure was chosen to identify weaknesses such as imprecise code definitions or overlaps of categories, and to revise the initial definitions of categories, anchor examples, and coding rules. Furthermore, the procedure helped to consolidate a common understanding of the categories between both researchers.

After revising the definitions of categories, anchor examples, and coding rules, we re-coded the transcripts using the revised version of the coding manual. In addition, three further transcripts were coded independently by two researchers. The coding were compared again and inter-coder reliability was tested according to the method proposed by Holsti [84]. Scientists generally acknowledge that inter-coder reliability coefficients of "0.8 or greater would be acceptable in most situations" [85] (p. 145). In explanatory studies, even values over 0.7 are regarded as tolerable [86,87]. In our case, the overall inter-coder reliability coefficient for all categories was 0.87 and between 0.81 and 1.00 for single categories. Since inter-coder reliability was acceptable, the remaining transcripts were coded according to the final coding manual. In the last step, we identified the information that was relevant for answering the research questions and summarized this material.

The preliminary results of the qualitative content analysis were discussed in a workshop with 18 stakeholders. The stakeholders participating in the workshop included different experts from breeding, seed production, cultivation, agricultural trade, food production, feed production, science, and public authorities. Four of the interviewees also participated in the workshop.

4. Results

The results section is structured according to the analyzed breeding goals and value-added steps. First, we present the results regarding the use of fungal resistant wheat. Based on the analysis of the interviews, we describe the requirements and actors´ motives to use fungal resistant wheat. Then, we describe the expected benefits, additional costs, and the potential economic risks. This is done for each of the value-added steps analyzed. The results regarding the use of coeliac-safe wheat are presented in the same way. We then describe the potential drivers and barriers for using fungal resistant and coeliac-safe wheat. Finally, we describe the challenges that arise from the regulation of genome-edited crops according to the European GMO legislation.

4.1. Fungal-Resistant Wheat

4.1.1. Breeding

In plant breeding, profound genetic knowledge as well as access to laboratory equipment are basic requirements in order to apply GE for developing new crop varieties such as fungal-resistant or coeliac-safe wheat. Another requirement from the viewpoint of breeders is that the *breeders' exemption*—which allows breeders to use protected varieties for breeding new varieties—must not be adversely affected by potential patents on GE. Furthermore, it is essential that GE in crops is accepted by society.

The interviewees consider GE to be a new instrument, which complements existing breeding techniques rather than replacing them. The main motive of breeders to apply GE is the expectation of accelerating breeding processes and increasing the sale of varieties due to improved traits.

A benefit from applying GE for crop improvement is the lower risk of negative correlations between the desired crop traits (e.g., resistance to fungal diseases) and other positive traits such as yield potential. Furthermore, introgression of undesired traits is less likely and the number of necessary backcrosses can be reduced compared to conventional breeding methods. This may contribute to finding solutions for agronomic problems such as fungal diseases quicker. According to the interviewees, there are no additional costs and economic risks associated with the use of fungal-resistant wheat provided that genome-edited crops are not regulated as GMO.

4.1.2. Seed Production

For seed producers, it is important that fungal-resistant wheat varieties meet the expectation of farmers regarding yield potential and other desired characteristics of wheat (e.g., winter hardiness). Furthermore, it is required that GE is accepted by society and that potential issues of patents are clarified. The motives of seed producers to reproduce fungal-resistant wheat varieties include the expectation of increasing seed sale, especially the sale of certified seed.

The benefits from reproducing fungal-resistant wheat include the opportunity to increase the portfolio of varieties and to improve the sales prospects of seed. Furthermore, seed producers can benefit from the lower risk of losing yields and reduced applications for fungicides. The interviewees do not expect any additional process steps due to the use of fungal-resistant wheat in seed production. Increased costs arise if seed producers have to pay breeders higher license fees for reproducing fungal-resistant wheat.

Economic risks for seed producers can result from the negative perception of GE in society. Additionally, seed producers may experience difficulties in marketing their produce if fungal diseases do not occur in certain years and there is less demand for fungal-resistant wheat varieties.

4.1.3. Crop Production

Several requirements must be satisfied to adopt fungal-resistant wheat in the value-added step of crop production. First, the varieties need approval according to the German Seed Act. Second, the varieties must be compatible with existing production methods and perform with high yields and quality. Third, the varieties must be available to farmers, i.e., seed producers must produce and distribute them. Ideally, the varieties should be offered by a multitude of seed suppliers since farmers prefer to select among a wide range of suppliers. Fourth, there must be a significant demand of traders and processors for the varieties. Fifth, GE must be accepted by society. In particular, it is important, from the farmers' point of view, that the cultivation of genome-edited crops is accepted by local actors including communities, residents, and landowners.

The main motive for farmers to cultivate fungal-resistant wheat is the expectation of facilitating wheat production by lowering the risk of infections with fungal diseases. Furthermore, farmers expect to increase the economic viability of wheat production by reducing the costs for plant protection measures. Other motives include the interest of individual farmers in testing innovative varieties and to make production methods more sustainable and environmentally friendly.

The availability of fungal-resistant wheat can lead to significant changes in the value-added step of crop production. The interviewees expect an increase in the competitiveness of wheat production, which can lead to an expansion of wheat production at the expense of other crops and crop rotations containing a multitude of different crops. Furthermore, the interviewees expect a decrease in approvals of chemical plant protection products since fungal-resistant wheat presents an environmentally friendly alternative.

The main benefit of producing fungal-resistant wheat is the opportunity to reduce the risk of yield losses due to fungal diseases and to reduce the applications for fungicides. The decrease in the use of fungicides leads to reduced residues of fungicides in crops and to savings in the costs for fungicides, labour, and machinery. Moreover, the more environmentally friendly production method and the decrease in residues of fungicides can contribute to improving the image of farmers and the sales prospects of their produce.

Higher costs for farmers accrue if seed prices increase. The interviewees expect no economic risks associated with the cultivation of fungal-resistant wheat provided that the resistance is not correlated with lower yields.

4.1.4. Agricultural Trade

According to the interviewees, no specific requirements have to be fulfilled for using fungal-resistant wheat in the value-added step of agricultural trade. The main motive of agricultural traders for using fungal-resistant wheat is the expectation of reducing the risk of mycotoxins in wheat. Furthermore, agricultural traders expect to reduce the efforts for cleaning and disposing of wheat lots contaminated by mycotoxins.

The interviewees state that the use of fungal-resistant wheat will probably not reduce the frequency of mycotoxin analysis since contractual agreements with business partners and legal regulations prescribe the duty for traders to quantify the mycotoxin levels in their lots. Mycotoxins impede the flexible trading of wheat since traders have to consider different maximum and guidance levels for mycotoxins when selling wheat to producers of food, feed, and industrial products. One benefit of using fungal-resistant wheat is the opportunity to trade wheat in a more flexible manner to different users (e.g., food producers, feed producers, biofuel producers). Another benefit is the lower risk of losing feedstock and profits due to mycotoxins. Additionally, the use of fungal-resistant wheat can lead to savings in the costs for cleaning and disposing of mycotoxin-contaminated wheat lots.

The interviewees do not expect any additional process steps and risks due to the use of fungal-resistant wheat in agricultural trade. Additional costs accrue if traders have to pay farmers a higher producer price for fungal-resistant wheat.

4.1.5. Milling

Social acceptance and especially the acceptance of GE by food retailers are essential requirements for using fungal-resistant wheat in the value-added step of milling. The motive for millers to use fungal-resistant wheat is the possibility of using inputs that are free of fungal diseases and residues of fungicides.

One benefit of using fungal-resistant wheat is that millers can reduce the frequency of mycotoxins analysis and the efforts of mitigation treatments (i.e., sorting and washing). This leads to savings in the costs for laboratory analysis, management, and energy. Using fungal-resistant wheat can also reduce the risks of losing wheat inputs due to mycotoxins. Furthermore, it can reduce the costs associated with the disposal or alternative use of mycotoxin-contaminated wheat (e.g., as input for feed and energy production). Other benefits for millers include the possibility of improving customer satisfaction and loyalty due to the better quality of milling products in terms of concentrations of mycotoxins and residues of fungicides. However, the interviewees do not expect buyers of milling products to be willing to pay a price surcharge for the quality improvement.

According to the interviewees, there are no additional costs and risks associated with the use of fungal-resistant wheat in the value-added step of milling.

4.1.6. Food Production

Several requirements have to be satisfied in order to use fungal-resistant wheat as input for food production. First, the quality parameters (e.g., protein content) and processing characteristics of wheat must not deteriorate due to GE. Second, fungal-resistant wheat must fit into the existing processing steps of food production readily. Third, GE should have a positive connotation in society and should not be linked to GMO.

The main motive of food producers to use fungal-resistant wheat is the expectation of reducing food waste and to achieve a smoother running of the food value chain. Additionally, food producers expect less conflicts with public authorities and buyers due to mycotoxins in food.

The benefits for food production are partly congruent with the motives and include the reduction of food waste, safer feedstock supply, and a more stable value chain. Fungal-resistant wheat can lead to cost savings if food producers reduce the frequency of analyzing wheat inputs for mycotoxins. Another benefit is the lower risk of additional costs and losses of added value in cases where wheat inputs containing mycotoxins have to be disposed of or used for less profitable purposes (e.g., as input for feed production). The interviewees do not expect food producers to benefit from higher producer prices since food must always comply with the regulations regarding concentrations of mycotoxins.

Additional costs accrue if food producers need to adapt the quality control measures for incoming wheat inputs to fungal-resistant wheat. However, the interviewees estimate the adaptation costs to be low. An excess demand for fungal-resistant wheat can result in procurement problems and higher feedstock prices which the interviewees perceived as economic risk.

4.1.7. Starch Production

There are no specific requirements for using fungal-resistant wheat in the value-added step of starch production except social acceptance of GE. One motive of starch producers to use fungal-resistant wheat is the expectation of benefiting from a greater regional supply of high-quality wheat. Another motive is the possibility of reducing the frequency of analyzing wheat inputs for mycotoxins.

The main benefit for starch producers is the higher stability of feedstock supply. Another benefit is the possibility of reducing difficulties in marketing the by-products of starch production (i.e., bran and gluten) due to mycotoxins and residues of fungicides. However, the interviewees state that starch producers are not able to earn any additional revenues for compliance with food and feed regulations. The willingness of starch producers to pay a price surcharge for fungal-resistant wheat is low since buyers of starch products would not pay a surcharge for compliance with the limit values for mycotoxins contamination.

According to the interviewees, there are no additional costs and economic risks associated with the use of fungal-resistant wheat in starch production.

4.1.8. Feed Production

The basic requirement for using fungal-resistant wheat in the value-added step of feed production is that GE is accepted by society. Another requirement is that the resistance to fungal diseases is reliable and that varieties are available in large quantities at any time of the year. Furthermore, it is important that there is no significant increase in the feedstock price of wheat. The main motive for feed producers to use fungal-resistant wheat is the expectation of reducing costs resulting from mycotoxins in feed production. The costs include the costs of analyzing wheat inputs for mycotoxins and the costs of sorting wheat in cases of mycotoxins detection.

The main benefit of using fungal-resistant wheat is that feed producers can reduce the frequency of mycotoxins analysis and the efforts of sorting wheat. However, the cost savings resulting from the reduction of sampling and sorting are estimated by the interviewees to be low.

According to the interviewees, there are no additional costs associated with the use of fungal-resistant wheat in feed production except the potential increase in feedstock prices. Furthermore, there are no specific economic risks related to the use of fungal-resistant wheat in feed production.

4.1.9. Animal Production

The main requirements for using fungal-resistant wheat in pig and cattle production include social acceptance and approval of the varieties for feed use. Furthermore, it is important that the potential increase in the price of feed containing fungal-resistant wheat is only moderate. Improving animal welfare, reducing the use of antibiotics, and the expectation of saving costs are the main motives of pig and cattle producers to use feed produced from fungal-resistant wheat.

The benefits of using fungal-resistant wheat as feed include the improvement of animal welfare and the lower risk of poor animal performance (e.g., low milk yields, low weight gain) and extended production periods due to disorders resulting from mycotoxins in feed. Furthermore, animal producers can reduce the risk of animal losses (e.g., piglets, gilts) to poisoning. Potential cost savings include a reduced need to treat sick animals. The treatment costs include labor costs for observing and separating sick animals as well as costs of antibiotics, vitamins, and absorbents. Benefits for the environment include the reduction of pharmaceutical residues in manure and the reduction of CO_2 emission due to improved feed conversion.

Additional costs accrue if animal producers have to pay higher prices for feed containing fungal-resistant wheat than for conventional feed. Furthermore, pig and cattle producers may experience difficulties in marketing their produce due to lacking acceptance of genome-edited crops by dairies, slaughterhouses, and food retailers.

4.1.10. Biofuel Production

Two requirements need to be fulfilled in order to use fungal-resistant wheat as feedstock in the value-added step of biofuel production. First, the respective varieties must be available in large quantities. Second, it is vital that the varieties meet the specific quality and processing parameters for biofuel production.

According to the interviewees, fungal diseases in wheat affect biofuel production since they increase the market price of feedstock due to the reduced supply of high-quality wheat. Furthermore, mycotoxins can build up at high concentration rates in the by-products of biofuel production (e.g., dried stillage) [88], which is a barrier for marketing the by-products as feed. The motive of biofuel producers to substitute conventional wheat for fungal-resistant wheat is to increase the possibility of marketing the by-products as high-quality feed and to avoid yield losses due to mycotoxins in feed.

From the viewpoint of the interviewees, fungal-resistant wheat can contribute to smoother feedstock procurement in biofuel production since it increases the supply of high-quality wheat. Another benefit is the possibility to reduce the frequency of analyzing wheat inputs for mycotoxins. The interviewees do not expect that biofuel producers can obtain higher prices for the better quality of the by-products since feed must always comply with the limit values for mycotoxins.

The interviewees expect an increase in the feedstock price because of the better quality of fungal-resistant wheat. Additional costs accrue if processing fungal-resistant wheat is more complicated than processing conventional varieties (e.g., due to increased use of enzymes).

4.1.11. Overview

Figure 2 provides an overview of the main costs and benefits of using GE and fungal-resistant wheat in the value-added steps of breeding, seed production, crop production, agricultural trade, and processing.

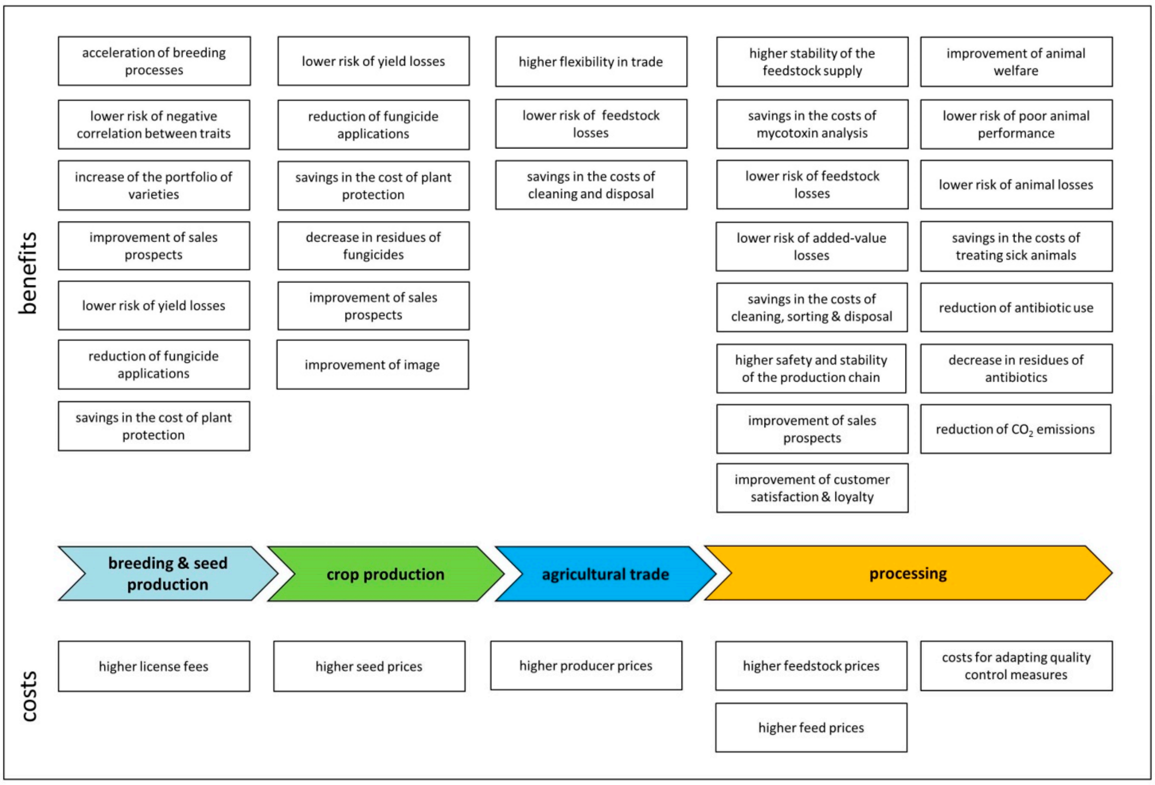

Figure 2. Overview of the costs and benefits of using genome editing (GE) and fungal-resistant wheat.

4.2. Coeliac-Safe Wheat

4.2.1. Breeding

The requirements and breeders' motives for using GE for developing coeliac-safe wheat varieties, the costs, and benefits, as well as the potential economic risks largely correspond to those described in Section 4.1.1.

4.2.2. Seed Production

The requirements for reproducing coeliac-safe wheat are similar to those for fungal-resistant wheat and include the social acceptance of GE, the clarification of potential patents issues, as well as the fulfillment of the expectations of seed producers and farmers regarding yield potential and other desired characteristics of wheat. Furthermore, the reproduction of coeliac-safe wheat must be strictly separated from the reproduction of other wheat varieties to avoid admixtures and to guarantee that farmers, processors, and consumers receive the varieties and products that they expect.

The motives of seed producers to reproduce coeliac-safe wheat varieties include the expectation of increasing seed sales. The benefits include the opportunity to increase the portfolio of products, the basis of customers, and to improve the sales prospects of seed due to quality improvement.

Additional costs can result from higher license fees for reproducing coeliac-safe and from the necessity to strictly separate the production, storage, and transportation of coeliac-safe wheat from other wheat varieties. The main economic risk for seed producers is the accidental mixing of coeliac-safe wheat seed with seed of other wheat varieties, which can lead to dead stock.

4.2.3. Crop Production

For many aspects, the requirements for cultivating coeliac-safe wheat do not differ from those described for the cultivation of fungal resistant wheat varieties (see Section 4.1.3).

A specific requirement for cultivating coeliac-safe wheat results from the necessity to guarantee the purity of varieties when delivering crops to traders and processors. Farmers need to align their whole crop rotation with the cultivation of coeliac-safe wheat to guarantee homogenous production. Furthermore, they must implement measures to avoid admixtures of other wheat varieties while harvesting, transporting, and storing crops. Such measures can include adequate cleaning of machinery between the harvesting and transporting of coeliac-safe and other wheat varieties as well as the establishment of separate storage facilities. Another possible requirement is the conclusion of a contractual agreement between farmers and buyers in which the buyers commit to purchasing the produce of the farmers at fixed prices.

The main motive of farmers to adopt coeliac-safe wheat is the opportunity to produce for a niche market and to benefit from the production under contracts. Another motive is the interest of individual farmers to improve the life of patients suffering from coeliac disease.

A potential change in the value-added step of crop production is the increase in direct wheat sales from farmers to processors (e.g., milling companies) due to contract farming. The main benefit for farmers results from the production under contracts and includes the guaranteed purchase of the farmers produce at fixed and high prices by the contractual partners. Moreover, farmers can increase their share in the added value from wheat production since the production under contracts offers the opportunity to sell wheat directly to processors without involving intermediate traders.

Additional costs can arise from higher seed prices and from the separate harvesting, transporting, and storage of coeliac-safe wheat. A specific problem of cultivating coeliac-safe wheat can arise if seed of other previously grown wheat varieties remain in soil and lead to volunteer plants. Volunteer plants in cultivating coeliac-safe wheat represent an economic risk for farmers since their removal is difficult and costly. Other risks include the admixture of other wheat varieties during harvesting, transportation, and storage of coeliac-safe wheat.

4.2.4. Agricultural Trade

Agriculture traders who sell coeliac-safe wheat to processors must guarantee the varietal purity of their produce. Separate purchase, storage, and transportation of coeliac-safe wheat is therefore a fundamental requirement for using coeliac-safe wheat in the value-added step of agricultural trade. Furthermore, it is essential that trade partners establish agreements regulating liability issues in the case of admixtures.

The motive of agricultural traders to use coeliac-safe wheat is to meet the feedstock demand of processors who produce specific food for consumers suffering from coeliac-disease. The main benefit for traders is the possibility to yield a higher market price for wheat due to the special quality of coeliac-safe wheat.

Additional costs can result from investments in separate storage capacities, cleaning of existing facilities, and the separate purchase and transportation of coeliac-safe wheat. The main economic risk is the admixture of other wheat varieties to coeliac-safe wheat which can lead to dead stock.

4.2.5. Milling

Several requirements need to be fulfilled in order to use coeliac-safe wheat in the value-added step of milling. First, there must be a significant demand for milling products suitable for consumers suffering from coeliac disease. Second, millers need suppliers who can reliably supply pure inputs of coeliac-safe wheat, i.e., inputs that are free from admixtures of other wheat varieties. In addition, millers must be able to check whether wheat inputs are purely composed of coeliac-safe wheat varieties. Third, the varieties must meet the specific quality parameters of milling and the expectations of buyers regarding the baking properties of wheat. Fourth, the processing of coeliac-safe wheat must be strictly separated from the processing of other varieties in order to avoid admixtures. Fifth, it is crucial that GE is socially accepted.

The motive of millers to process coeliac-safe wheat is to meet the demand of consumers for products suitable for coeliac-disease. The benefits include the possibility to increase the portfolio of products that can be sold to consumers with coeliac disease. Furthermore, millers can benefit from producing products that can generate a higher added value.

Additional costs can result from the potential increase in the feedstock price of wheat and from separately purchasing and processing coeliac-safe wheat. Furthermore, additional costs can arise from investments in separate production lines or complex cleaning processes between the processing of coeliac-safe wheat and other wheat varieties.

The main economic risk associated with the use of coeliac-safe wheat is the admixture of other wheat varieties during the processing of wheat. Furthermore, there is the risk that changes in consumer behavior lead to a decrease in the demand for coeliac-safe products.

4.2.6. Food Production

For food production, coeliac-safe wheat should have the same characteristics as conventional wheat with regard to quality and processing parameters. Furthermore, it is essential that GE is accepted by society and that coeliac-safe wheat is compatible with the existing processing steps of wheat.

The main motive of food producers to process coeliac-safe wheat is the expectation of benefiting from higher market prices for coeliac-safe food. Another potential motive is the interest of individual food producers in improving the quality of life of patients suffering from coeliac disease.

An economic and social benefit from using coeliac-safe wheat as input for food production is the possibility to increase the range of products that can be sold to consumers suffering from coeliac disease.

Additional costs can result from separating the processing of coeliac-safe wheat from the processing of other wheat varieties. An excess demand for coeliac-safe wheat can lead to procurement problems and higher feedstock prices, which the interviewees considered an economic risk.

4.2.7. Starch Production

Various requirements must be met in order to use coeliac-safe wheat in the value-added step of starch production. First, there must be a demand for coeliac-safe starch and the respective wheat varieties must be available in sufficient quantities and in uniform quality. Second, it is vital for starch producers that there is no significant increase in the feedstock price of wheat. An increase in the price of wheat poses a risk for producers of wheat starch since it decreases the competitiveness of wheat starch against other types of starch, especially maize starch. Third, the by-product gluten must remain marketable since the revenues from gluten sales are indispensable for the economic viability of wheat starch production. This also includes that the baking quality of the by-product gluten remains high. Fourth, starch producers must guarantee the strict separation between the processing of coeliac-safe wheat and other varieties of wheat to avoid admixtures.

Using coeliac-safe wheat is only an option for specialized starch producers who aim to produce coeliac-safe food products. The motive of the producers to substitute coeliac-safe wheat for conventional wheat is to increase the portfolio of products and to meet the demand of consumers for coeliac-safe products.

The main benefit for starch producers is the possibility of saving the cost of applying special techniques for producing gluten-free wheat starch. The savings in production costs can increase the competitiveness of wheat starch compared to naturally gluten-free starches (e.g., maize and potato starch), which presents another benefit of using coeliac-safe wheat.

Additional costs can result from the potential increase in the feedstock price of wheat, from investments in separated production lines, and from cleaning processes between the processing of coeliac-safe wheat and other wheat varieties. According to the interviewees, the costs of separation can be prohibitive.

The main economic risk associated with the use of coeliac-safe wheat is the potential decrease in sales of starch in the market for gluten-free bakery products. Gluten-free wheat starch mainly serves as a substitute for flour in the production of gluten-free bakery products due to its positive baking properties. However, bakeries would not substitute gluten-free wheat starch for flour if wheat flours are available that do not trigger coeliac-disease. Another risk is the decrease in the value of acquired know-how on producing gluten-free wheat starch.

4.2.8. Overview

Figure 3 provides an overview of the main costs and benefits of using GE and coeliac-safe wheat in the value-added steps of breeding, seed production, crop production, agricultural trade, and processing.

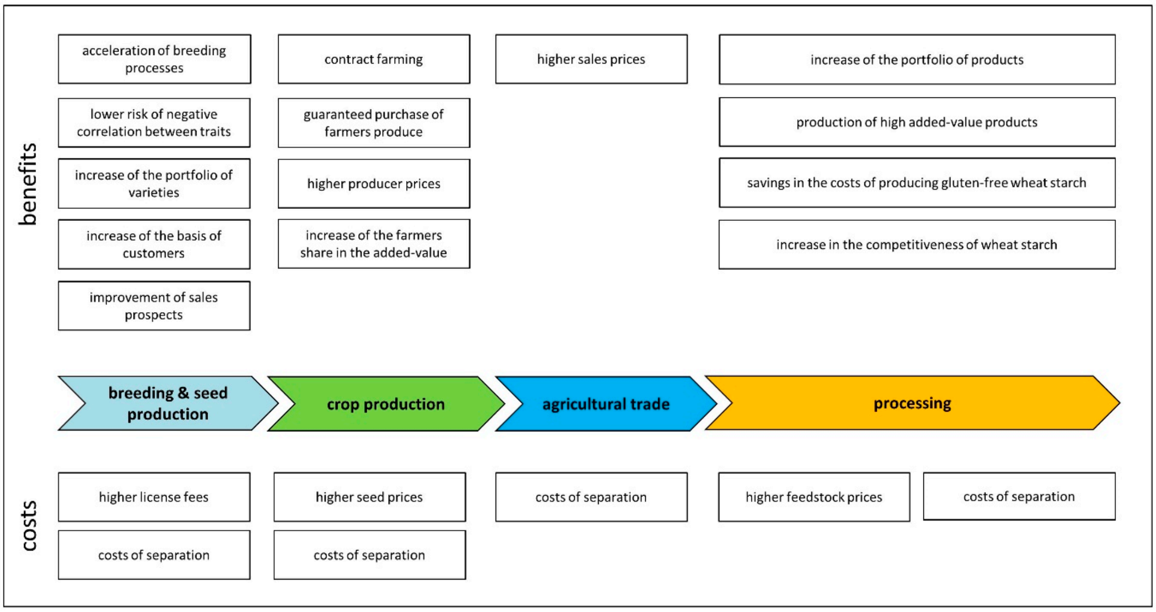

Figure 3. Overview of the costs and benefits of using genome editing (GE) and coeliac-safe wheat.

4.3. Drivers and Barriers

In the following section we provide an overview of the drivers and barriers for GE perceived by the stakeholders in the value chains of wheat. First, we present the general drivers and barriers for GE in crops. Then, we describe the specific drivers and barriers for using fungal-resistant and coeliac-safe wheat.

Some of the stakeholders interviewed regard patents as a general driver for GE provided they allow access to innovations under fair conditions and do not adversely affect existing plant breeders' rights including the *breeders' exemption*. Other stakeholders regard the economic interest of farmers and industrial entrepreneurs of using improved crops as a driver for GE in crops. The interviewees state that the main barrier for adopting genome-edited crops in agricultural value chains is the low acceptance of GE by society and food retailers. Farmers and processors are afraid of damaging their image when they cultivate and process genome-edited crops. In particular, they fear potential media campaigns against them. From the viewpoint of seed producers and farmers, barriers arise from the uncertainties regarding the patentability of genome-edited crops. Farmers fear that potential patents on GE could promote monopoly situations and restrict the farmers' privilege to reuse protected seed. Other barriers for cultivating genome-edited crops include the possible refusal of landowners for the cultivation of genome-edited crops on leased land and the reluctance of processors to compensate farmers for increased seed costs through higher producer prices. The interviewees also state that the market power of food retail to establish its own labeling and the long time needed for scientific analysis and evaluation hampers the adoption of genome-edited crops.

Specific drivers for the adoption of fungal-resistant wheat are the problems and costs caused by fungal diseases and mycotoxins along the different steps in the value chains of wheat. Another driver is the increase of restrictions for applying fungicides in crop production. Farmers experience a decrease in the number of approved active substances and in the effectiveness of existing plant protection products. As a consequence, farmers need to find alternative solutions for controlling fungal diseases. Fungal-resistant wheat presents such an alternative. A further driver for adopting fungal-resistant wheat is the societal demand for better animal welfare conditions and environmentally sound production methods. A potential barrier for using fungal-resistant wheat is the existence of alternative strategies for controlling fungal diseases and mycotoxins (e.g., fungicides, cleaning, sorting). Another is the low interest of consumers to reduce the problems caused by fungal diseases in the value-added steps of crop production and processing. The interviewees state that consumers do not perceive any personal benefit from using fungal-resistant wheat in crop production.

A specific driver for adopting coeliac-safe wheat is the increasing societal trend to consume gluten-free food. The interviewees state that even consumers who do not actually suffer from coeliac disease would buy coeliac-safe products, which is an additional incentive for producers to enter the market. Potential barriers for adopting coeliac-safe wheat include the high cost of separating the production and processing of coeliac-safe wheat from other varieties of the wheat in order to avoid admixtures. Lacking confidence in the technical feasibility of the separation presents another possible impediment since it can cause mistrust between the actors in the value chain. Moreover, consumers may be reluctant to buy coeliac-safe wheat products if they are convinced that products containing wheat are not suitable for patients suffering from coeliac disease.

4.4. Challenges

This chapter focuses on the challenges that arise from the regulation of genome-edited crops according to the European GMO legislation. The interviewed stakeholders from breeding and seed production expect many uncertainties, especially regarding future regulation, duration of approval processes, or restrictions regarding applications. Most of the interviews were carried out while the legal proceedings at the ECJ were still pending. Breeders and seed producers see a major challenge in the detection and identification of GE along the value chain and the need to establish separate production chains in order to avoid admixtures. In contrast to classical genetic engineering, they perceive GE as a technology that can be used by small or medium-sized companies at comparably low costs. However, the interviewees expect that regulation is likely to distort the competition among small, medium, and large companies. Experiences from GMO regulation showed negative effects of labeling seed on marketing and acceptance. Stakeholders fear similar developments should comparable regulations for genome-edited seeds be introduced.

The challenge of establishing separate production chains is seen by stakeholders from crop production as well. When it comes to commodities, separation of different lots can be costly and might not be feasible for every farmer. The perception differs between the two breeding goals, since for coeliac-safe wheat, the identity preservation of the product is essential, and a separate production chain has to be established anyway. Labeling of genome-edited products is also perceived as a challenge by interviewees from the crop production sector.

The challenges of detection and identification on the one hand and separation on the other are also relevant for stakeholders from agricultural trade as well as from food and feed production. Although costly and not applicable to commodities, interviewees assume that separating and labeling coeliac-safe wheat is economically justifiable in order to guarantee the identity of the product and to yield a higher market price.

5. Discussion

In the following section, we will discuss the empirical findings from analyzing the impact of GE on the value chains of wheat in Germany. We start with discussing the findings according to the research questions. After this, we will reflect upon the lessons learned for implementing genome-edited crops in agriculture. Finally, we will discuss the research design and suggest potential directions for future research.

5.1. Empirical Findings

The results of the case analysis of the value chains of wheat show that several requirements must be fulfilled in order to use fungal-resistant and coeliac-safe wheat. In accordance with other studies [46,47], our findings highlight that social acceptance of GE in crops is indispensable for using genome-edited crops in agriculture value chains.

We observed that actors in the value chains of wheat have different motives for using genome-edited crops. The main motives for actors to use fungal-resistant wheat include the expectation to reduce the problems and costs resulting from fungal diseases and mycotoxins. The main motive for actors to use coeliac-safe wheat is to meet the demand of consumers for products suitable for coeliac-disease sufferers. However, in the case of fungal-resistant wheat, the results also show that the interest in testing innovative varieties, the expectation of improving animal welfare, and to making production methods more environmentally friendly motivates actors to use genome-edited crops. This finding may suggest that the use of genome-edited crops in agricultural value chains is not only driven by economic motives.

Another observation made in this study is that the actors in the value chains of wheat expect significant benefits from using fungal-resistant and coeliac-safe wheat at each step of the value chain. Fungal-resistant wheat benefits actors by reducing the problems and costs resulting from fungal diseases and mycotoxins. Coeliac-safe wheat mainly benefits actors by producing products that can generate a higher added-value. The findings lend empirical support to the study of Lassoued et al. [14] who highlighted the potential of GE for producing crops with higher agronomic performance and product quality. In addition, the findings suggest that the use of genome-edited crops does not only provide benefits for actors in agricultural value chains. Fungal-resistant and coeliac-safe wheat can also benefit society and the environment. The social benefit of coeliac-safe wheat is the opportunity to increase the portfolio of products that are suitable for consumers suffering from coeliac-disease. However, empirical studies showed that only about 1% of the population in Europe suffers from coeliac disease [71]. The social benefit of using coeliac-safe wheat is therefore limited to a small part of society. However, Kucek et al. [89] consider research efforts to identify, develop, and label less-reactive wheat genotypes as suitable options for improving the diets of coeliac and wheat sensitive individuals and populations. By contrast, fungal-resistant wheat provides benefits to society as a whole. The findings show that fungal-resistant wheat can contribute to meeting societal demands for reduced food waste, improved animal welfare conditions, and reduced application of antibiotics in animal production. Furthermore, the results show that fungal-resistant wheat can contribute to making crop production methods more environmentally friendly by reducing the application of fungicides. However, findings of empirical studies suggest that farmers who grow disease-resistant wheat may not reduce the application rate of fungicides. Klocke and Dachbrodt-Saaydeh [90] showed that the share of disease-resistant wheat varieties grown on farms has increased over the last years in Germany. However, the treatment frequency index (TFI) indicating the fungicide use intensity did not decrease at the same time. Farmers tend to treat resistant and non-resistant wheat in the same way since they want to optimize labor and machinery time and are often not aware of the fungal-resistance. Therefore, the availability of fungal-resistant wheat may not necessarily lead to the expected benefits but requires additional support and advice for farmers on the environmental and economic advantages of new varieties.

The benefits of using fungal-resistant and coeliac-safe wheat may not be distributed evenly among the different steps of the value chain. In the case of fungal-resistant wheat, we argue that the distribution of the benefits depends on the potential yield losses and costs caused by fungal diseases and mycotoxins at every step of the value chain. Fungal-resistant wheat may provide a greater benefit to those steps in which fungal diseases and mycotoxins lead to substantial yield losses and costs. Fungal diseases and mycotoxins mainly affect yields and costs in the value-added steps of crop production, agricultural trade, milling, and animal production. By contrast, the value-added steps of food production and starch production are less affected by fungal diseases and mycotoxins since the control of fungal diseases and mycotoxins mainly takes place at upstream steps of the value chain. Food and starch producers only use inputs of wheat that comply with the limit values for concentrations of mycotoxins. Therefore, fungal-resistant wheat may provide a greater benefit to crop producers, agricultural traders, millers, and animal producers. In the case of coeliac-safe wheat, we argue that the distribution of the benefits among famers, agricultural traders, and processors depends on the sales strategy for coeliac-safe wheat. Farmers may obtain a higher share of added-value if they sell coeliac-safe wheat directly to processors. In this case, agricultural traders would not participate in the value chain and therefore could not siphon off any share of the added value.

The use of genome-edited crops may lead to additional costs for the actors in agricultural value chains. Our findings indicate that higher license fees in seed production, higher feedstock prices, and higher product prices in the value-added steps of processing wheat increase costs. In addition, the findings show that separating the production and processing of coeliac-safe wheat from other wheat varieties causes additional costs. The costs of separation may be prohibitive. We argue that higher market prices for coeliac-safe products are therefore indispensable in order to compensate actors for the costs resulting from higher feedstock prices and the separation.

We believe that the cost and benefits of using genome-edited crops will greatly depend on the development of the price of genome-edited crops compared to the price of conventional crops. Furthermore, we assume that the cost and benefits will depend on the price transmission along the value chain. The findings show that the actors in the value chains of wheat expect an increase in the feedstock price of wheat leading to higher feedstock costs. Higher prices of wheat-based products can compensate actors for higher feedstock costs. However, in the case of using fungal-resistant wheat, in the value-added steps of milling, starch production, and biofuel production, the results indicate that buyers of wheat-based products may not accept higher product prices. In such cases, it is particularly important that the benefits resulting from the lower risks of mycotoxins are sufficiently high in order to secure the profitability of using fungal-resistant wheat.

Economic risks can pose a significant barrier for using innovations in agricultural value chains like GE. Based on the assumption that genome-edited crops are not regulated as GMO, our results suggest that the actors in the value chains of wheat expect only a few economic risks when using fungal-resistant wheat. The risks include potential difficulties in marketing products due to a lack of acceptance of genome-edited crops by buyers. Furthermore, the risks include the potential imbalance between the demand and the supply for fungal-resistant and coeliac-safe wheat. However, we argue that imbalance between demand and supply for crops represents a normal market situation, which is not specific to the use of genome-edited crops. We observed that the main economic risk of using coeliac-safe wheat is the potential admixture of other wheat varieties during the production and processing of coeliac-safe wheat. Accidental gluten admixture from other wheat varieties is a trigger for liability and redress. Therefore, all actors in the value chain must establish appropriate precautions in order to avoid admixtures. Stakeholders from crop production see contract farming as a suitable option. For instance, contractual arrangements between farmers and buyers of wheat could prohibit the cultivation of crops containing gluten on the areas in question in order to minimize the risk of volunteer plants.

The results regarding the drivers and barriers show, on the one hand, that the main barrier for adopting genome-edited crops in agricultural value chains is the lack of acceptance of GE by society and food retailers. On the other hand, they show that consumer trends and societal demands for better animal welfare conditions and environmentally sound production methods can be a driver for the adaptation of genome-edited crops. Based on this observation, we argue that better communication of the social and environmental benefits of genome-edited crops may help to improve the acceptance of GE by society. Better communication of the social and environmental benefits is particularly important for strengthening the acceptance of genome-edited crops like fungal-resistant wheat since they provide no direct benefits to consumers. Social acceptance may be easier to achieve for those crops that provide a direct benefit to consumers such as coeliac-safe wheat.

The study also points towards some challenges resulting from GMO regulation. The results show that innovation in the value chain—such as the introduction of a fungal-resistant or coeliac-safe wheat variety—can lead to benefits and additional costs. For example, the innovative product characteristic of coeliac-safe wheat entails additional costs for separating and maintaining product identity, in order to avoid damage and liability. The costs may be offset by the fact that higher product prices can be expected. Here, the focus lies on the product characteristic, which represents a direct benefit to the consumer. Against the background of a GMO regulation, there may also be requirements regarding separation, traceability, labeling, and liability. However, these requirements will probably only have a minor impact on the value chain, since a private regulation for ensuring the product's identity along the value chain needs to be implemented in any case. Whether further costs arise in practice under these conditions needs to be analyzed in future studies.

The situation is different for the case of fungal-resistant wheat. This purely agronomic trait primarily aims at reducing the problems and costs resulting from fungal diseases and mycotoxins. In the interviews, however, the willingness to pay higher prices for a mycotoxin-free product, was classified as low. A consumer benefit—even if de facto given—is not perceived as such. This discrepancy has already been documented by Bt-maize, which also led to a reduced mycotoxin input into the feed chain [91]. In contrast to coeliac-safe wheat, regulation under the European GMO legislation may entail additional costs. Numerous studies have shown that agricultural production in particular is affected by the costs of ex-ante regulation and ex-post liability [31,32,92]. The costs comprise compliance of coexistence rules, such as isolation distances and other rules of good agricultural practice, which do not yet exist for the cultivation of GMO wheat in Germany [93]. Furthermore, it is now essential to separate the flow of goods along the chain and different batches of this commodity cannot be mixed to obtain certain qualities. Under these circumstances, an additional regulation—which aims at separating the flows of goods and labeling—may reduce trade flexibility and incur additional costs, including the need to establish an entirely new channel along the value chain. This has already been documented in the cultivation of GMO [33]. Past experience shows that the acceptance of GMOs in the food chain is low. To date, no GMO wheat has ever been approved worldwide, even though large plant breeding companies have already carried out trials with herbicide tolerant wheat, which is also a purely agronomic trait. In contrast to classical GMO—such as maize or soya, which are mainly used for animal feeding—wheat also enters the human food chain. For this reason, GMO traits that provide no consumer benefit have not been followed up in the past [94].

5.2. Lessons Learned and Contribution to the Literature

Several lessons can be learned from the case analysis of the value chains of wheat. The study shows that the adoption of crops developed by GE can lead to significant benefits for actors in agricultural value chains. Fungal-resistant wheat benefits actors by reducing the problems and costs resulting from fungal-diseases and mycotoxins. Coeliac-safe wheat benefits actors by producing high value-added products, which can be safely consumed by patients suffering from coeliac disease.

Referring to the case of fungal-resistant and coeliac-safe wheat we conclude that GE can contribute to mitigating agronomic problems, reducing costs, and enhancing the safety and quality of products in agricultural value chains. Another conclusion we draw from the case study is that GE can contribute to meeting societal demands for reduced food waste, better animal welfare conditions, and environmentally friendly production methods. However, we also conclude that social acceptance of GE is indispensable for using genome-edited crops in agricultural value chains. Low acceptance of GE by society and food retailers poses a significant barrier for adopting genome-edited crops in agricultural value chains. Better communication of the social and environmental benefits of genome-edited crops may help to strengthen acceptance.

Our study contributes to the literature in several aspects: First, it provides detailed insights into the potential costs and benefits of producing and using genome-edited crops in agricultural value chains. Second, it helps in understanding the requirements and the motives of actors' to produce and process genome-edited crops better. Third, it provides valuable insights into potential economic risks as well as the drivers and barriers for using genome-edited crops in agricultural value chains.

5.3. Research Design and Future Research Directions

The results refer to the hypothetical case of producing and processing genome-edited crops in the value chains of wheat in Germany and may not be generalized without critical reflection. Although fungal-resistant wheat and coeliac-safe wheat have not been developed yet, we believe that the findings of our study provide a solid basis of knowledge and information about the potential impact of GE on agriculture value chains. We acknowledge that more research is needed to prove whether the analyzed varieties are workable in practice.

The value chain concept formed an appropriate conceptual framework to help understand the potential impact of GE on agribusiness better. In particular, it was useful to identify the relevant actors, activities, and linkages between the different industries using wheat. Furthermore, the concept helped us to systematically scrutinize the impact of GE along the different steps of production.

The methods applied in this study are subjected to the general limitations of qualitative research such as the more complex collection and interpretation of data, the lower robustness of the data, and the limited generalizability of the results [95–97]. However, we argue that the case study strategy based on data from semi-structured interviews was appropriate for analyzing the impact of GE on agricultural value chains. The value chains of wheat proved to be an expedient case study since it allowed for in-depth analysis of the cost and benefits of using genome-edited crops in a wide range of industries and value-added steps. The face-to-face interviews were useful since they provided deep insights into the requirements and actors' motives for using genome-edited crops. Moreover, interviewing associations proved to be an efficient strategy to get a detailed overview of the analyzed industries and to learn about the specific characteristics of the associated value-added steps.

The analysis of the impact of GE on the value chains of wheat was a qualitative analysis, which focused on a detailed description of the cost and benefits. Further research is necessary to quantify the monetary cost and benefits of producing and using genome-edited crops. In addition, future studies should elaborate on the distribution of the economic risks and the cost and benefits among the actors and the different steps of agricultural value chains.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/22/6421/s1, Manuscript S1: Interview guideline, Table S1: Coding manual.

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