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Building consensus on demand-led legume breeding in Europe: Evidence from a Delphi expert study

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ABSTRACT

Legume breeding is of great importance due to the multiple benefits of legume cultivation and use in European food systems. However, the small legume acreage means that breeding programmes are often not economically viable. Improvements to the system could be initiated by the governance structure of demand-led breeding. Demand-led breeding is an approach in which the needs of stakeholders downstream of agriculture are explicitly considered to develop more appropriate varieties. To evaluate this approach, we conducted a Delphi study with 21 legume breeding experts from across Europe. Qualitative questions enabled indirect discussion, and the experts formed a group opinion through repeated quantitative ratings of statements on demand-led breeding. The data was analysed using qualitative content analysis and inferential statistics with a non-parametric rank variance analysis. Expert consensus emerged that breeding goals should be oriented towards the end use of the products, that demand-led breeding is more likely to become established in Europe in the medium term, and that better alignment with market demand can increase value creation in breeding. The complexity of breeding programmes would increase and the added value would only become apparent retrospectively after a time lag. We conclude with the implications that demand-led breeding may be implemented within the framework of vertical strategic alliances and development partnerships, but that this business model needs further research. We also recommend that research efforts should focus on establishing an information infrastructure within the legume sector and strengthening the links between breeding and the processing industry.

1. Introduction

Legumes and, consequently, legume breeding are of considerable relevance in the broader context of European food security [1]. The cultivated species of the *Fabaceae* family offer extremely versatile properties and performance characteristics [2]. Small-seeded legumes are well suited for sustainable animal feed production, humus formation and soil improvement [1]. Grain legumes are useful in both animal and human nutrition due to their high protein content and high digestibility [3,4]. The cultivation legumes is possible without additional nitrogen fertilisation measures due to the symbiotic fixation of atmospheric nitrogen and leads to an increase in biodiversity in natural landscapes [5]. They are one of the most important raw materials for producing plant-based meat and milk alternatives [3,6,7]. Legumes are therefore frequently featured in political and scientific discussions about the desired ecological transformation of agriculture and the food system [8–10]. However, with the exception of soybeans, they have remained minor crops in European agriculture for years, with less cultivation, processing, and demand than is possible [11].

Magrini et al. [7,12] attribute the niche situation of legumes to a variety of interacting and self-enforcing factors. These factors create a 'lock-in' situation, or path dependency. It implies difficult short- and medium-term changes in the food system. A lack of economic incentives for various stakeholder groups within legume value chains is a key factor [13]. The neglect of legumes in plant breeding is another factor [3,14]. Grain legumes account for only about 6% of the arable land available in the EU [15]. The limited acreage of legumes prevents viable breeding programmes in private companies [14]. Revenue from licence fees is insecure, hard to calculate, and insufficient to cover costs [16]. New governance structures and lucrative business models in the breeding industry could help to overcome this deadlock. A key lever within such new approaches is the stronger alignment of breeding decisions with the needs of downstream actors, as envisaged by the demand-led breeding (DLB) approach. DLB could create new demand through breeding progress or by addressing previously unmet needs along the value chain [17,18].

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DLB can serve as a tool in the context of an agricultural innovation system and has hardly been described scientifically in European environments. In Africa and Latin America, however, the concept is already known as an efficient value chain-orientated approach [19,20]. Against this backdrop, we examine the DLB approach for legumes in Europe for the first time and describe it based on relevant literature. In addition, our study aims to evaluate the potential and relevance that the breeding industry itself identifies in this concept. This addresses the research gap regarding which stakeholders, apart from agriculture, can provide the most important information needed for the optimal adaptation of breeding objectives to the diverse needs along the legume value chains. The selection of relevant downstream stakeholders seems to be an unknown variable [19]. It leads to the three-part research question: (1) Can a consensus be found among breeding experts on the assessment of the DLB approach and its potential relevance and implementation in European legume research and breeding? (2) What opportunities and risks are seen in the concept from a breeding perspective, and (3) which stakeholders along the value chain are the most important actors for providing the necessary information, and what are the most important topics on which demands and needs must be communicated? To this end, we conducted a multi-stage Delphi study as a participatory qualitative-quantitative method for recording the assessments of 21 European experts in legume breeding. In this context, the method is used as a social science policy tool for consensus building and for identifying priorities for action in the food value chain. They are needed for a potential system transformation to break path dependencies by the integration of demand-side impulses into legume breeding and research.

The novelty of the study lies in the systematic conceptual and empirical refinement of the demand-led breeding approach for the European legume context. While DLB has so far been addressed in the literature primarily in normative terms, this study shows which information-related and stakeholder-related requirements are relevant for the practical design from the perspective of breeding experts. The contribution is thus to conceptualise DLB not only as an abstract objective, but also as a specific coordination scheme along the value chain. Using the Delphi-Approach, the study reveals the interfaces between breeding, downstream market players and the institutional environment at which the potential for implementing DLB can be located. This is also where the theoretical contribution of the underlying study lies. The broader theoretical background to the socio-economic interfaces discussed in the context of demand-led breeding is presented in the following section.

2. Conceptual background

Demand-led breeding can be understood as an approach that might counteract the lock-in situation described in the legume sector [7,12]. On the breeding side, this lock-in situation arises primarily due to a lack of information on demanded quality. Downstream, path dependence is exacerbated by uncertainty regarding quality. The DLB approach can therefore be linked to socio-economic theories on information asymmetry. Following Akerlof, the fact that breeders receive only incomplete and uncertain information about use-related requirements from downstream market stages can be understood as a problem of asymmetric information. This makes it difficult to precisely define breeding objectives that meet market demand [21,22]. This can therefore also contribute to the existence of suboptimal market or innovation pathways or reduce the willingness to invest in plant breeding. To overcome this structural market failure, Akerlof's framework offers standardised solutions aimed at reducing information asymmetry through signalling and screening mechanisms. These can hypothetically be applied to the lock-in situation of legumes. On the demand side, this requires targeted screening by the processing industry, whereby it defines and communicates quality specifications (e.g. specific amino acid and protein profiles) ex ante to steer the breeding process in a targeted manner. Complementary to this, plant breeding can increase market transparency through strategic signalling by providing new legume varieties with processing-oriented independent certifications. Should these internal market mechanisms prove insufficient to lead the legume sector out of the lock-in situation, specialised variety branding or an adjustment to variety registration could constitute further measures in line with Akerlof. As a radical measure, extending DUS variety testing to include processing-related criteria could serve as an institutional bridge to resolve the lock-in dilemma and sustainably reduce transaction-specific uncertainties throughout the entire value chain [23,24].

However, DLB requires targeted coordination, trust-building and institutionalised information flows to reduce quality uncertainty along the value chain and to translate previously poorly articulated needs into breeding priorities. At the same time, DLB should be interpreted as part of a breeding innovation system in which several groups of actors with different functions, knowledge bases and resources are interdependent. Multi-stakeholder collaboration within the framework of breeding innovation systems demonstrates that innovative capacity arises precisely where public institutions, companies, research organisations and intermediary actors interact in an institutionalised manner and coordinate their contributions across different chains [25]. DLB can thus be understood as a mechanism within the innovation system that operates at the interface of knowledge integration, coordination and goal definition, thereby helping to transform information-asymmetric market conditions into innovation processes that can be collectively managed [26].

In the context of plant breeding, no direct customers or buyers can be identified in the traditional sense, as plant varieties and genetic material are not normal goods or services. According to Halewood [27], plant genetic resources for food and agriculture differ from both natural and man-made cultural resources. This means that classifying them as a public good does not cover all aspects. Instead, according to Halewood [27], the outputs of plant breeding are kind of hybrid goods with significant exclusion costs. According to Gerullis [28], following Hinkel et al. [29], these are also classified as collective goods. Consequently, the services and innovations of plant breeding are in demand not only from a definable group, but also serve complex private and social target groups. For this reason, there is a need to clarify the terminology used for customers of plant breeding, to which we add all actors or stakeholders who are downstream of breeding in the value chain and are touched by breeding changes in plant material. In the following, we will primarily use the term “stakeholder”, whereby all possible stakeholders together can be termed as “need cluster”. The understanding of the interactions and mutual influences between legume breeding and downstream market developments, as well as the interaction with the need cluster are important for the implementation of DLB.

Content-wise, demand-led breeding can be described as an approach to improving crops, in which breeding priorities are systematically aligned with the needs and preferences of various stakeholders throughout the agricultural and food value chain. While breeding traditionally focuses on traits relevant to cultivation, demand-led breeding expands the scope to include functional and qualitative traits that are important to stakeholders beyond primary agriculture [30,31]. These include, for example, feed manufacturers, food processors, retailers, and end consumers. The requirements of those are key to the acceptance of a variety and its market success [32]. The approach includes studies to prioritise traits and multi-criteria decision-making, to ensure that breeding investments deliver measurable benefits to all users [33]. This could promote innovations that are socio-economically relevant and contribute to resilient and sustainable food systems. This is possible through the targeted development of crop varieties that perform well agronomically and meet downstream market specifications. In developed regions such as Europe, where value chains are complex and highly segmented, demand-led breeding also aims to identify and prioritise target product profiles. These profiles translate stakeholder needs into feasible breeding goals through participatory and

data-driven processes [18].

DLB can therefore be understood as a sequentially structured translation and prioritisation process between the market, value chains and breeding. Assefa et al. explicitly describe this approach in the context of market-oriented legume breeding as a process in which breeding decisions are systematically linked back to utilisation contexts and market segments [19]. The conceptual core of DLB therefore lies in the targeted transformation of diffuse, often heterogeneous and sometimes implicit needs into target breeding profiles. These must be market-related, connectable and biologically and organisationally feasible [34]. This process is not linear, but iterative, as target profiles are repeatedly compared with information from market observation, stakeholder interaction and practical selection [31,32]. However, this only works if there are no information asymmetries and the business activities of the need cluster are not characterised by uncertainty regarding quality [21]. DLB thus describes less a single method than a coordination paradigm for the orientation of breeding. In this regard, breeding objectives do not arise in isolation at the variety level but must be defined in an interplay of agronomic performance, utilisation quality, stakeholder preferences and institutional framework conditions [20].

However, to integrate possible measures of breeding, selecting and testing into a breeding process, different breeding approaches or breeding models can be compared. These are characterised by different ways of defining objectives and involving different stakeholders [35]. In this context, DLB belongs to market-oriented and value chain-related breeding approaches that derive breeding objectives not only from agronomic performance requirements. This is described in the literature as a data- and knowledge-based process, thus establishing a central link between market information and breeding decisions [34]. DLB thus focuses primarily on the question of how breeding goals are defined ex ante, while related approaches are more focussed on certain forms of participation or practical testing [36]. This also becomes clear in comparison with participatory plant breeding and participatory testing approaches. Participatory plant breeding involves farmers directly in individual steps of the breeding process, for example in selection, scoring, phenotyping or site-specific evaluation. In this regard it primarily aims to utilise local knowledge, take greater account of regional contexts and increase the adaptability of varieties to specific production conditions. Furthermore, unlike DLB, these approaches have a local focus and aim to reduce costs in operational breeding activities [37,38]. Citizen science and group-based on-farm testing approaches extend these approaches by using digital or collectively organised forms of participation to record variety-related performance more systematically [33].

The difference to DLB, however, is that DLB understands the entire upstream process of target definition more as a coordination task across value chains. The focus is not only on the question of who is involved in breeding, but above all on which needs are translated into breeding targets and for which market segment [34]. Assefa et al. refer to this as a paradigm shift towards a value chain-focused approach with relatively less emphasis placed on the farmer-focused approach of a farmers engaged in selecting varieties [19]. The Participatory Ex-antE Framework for Plant Breeding (PEEP) can also be categorised against this background. PEEP is an ex-ante prioritisation framework designed to help link breeding priorities, product concepts and expected impacts in a multi-stage, multi-stakeholder process. While DLB forms the overarching orientation framework for the systematic alignment of breeding with demand and utilisation contexts, PEEP provides a methodological tool to structure this prioritisation in a participatory and impact-related manner [36].

DLB should therefore be considered in the context of breeding innovation systems. From the perspective of agricultural innovation systems, innovation does not arise within individual organisations, but through interactions between different stakeholders, forms of knowledge and institutional frameworks [26]. DLB is also related to Mission-oriented agricultural innovation systems. These emphasise that networks must be coordinated towards specific (societal) objectives and only develop gradually through stakeholder relationships, political support, funding structures and learning processes [39]. Against this background, DLB could be understood as a governance-oriented approach within such an innovation system and forms a connection between value chain governance, co-innovation and multi-actor breeding strategies. It links the question of which traits should be developed with the question of how corresponding knowledge can be collected, communicated, legitimised and ultimately transferred into breeding decisions [20,40]. This makes the entire system multi-layered. Lopes and Martha see great importance in governance structures in breeding processes [5]. Governance and policy are frameworks without which breeding cannot bridge the gap between scientific progress and effective technological and knowledge implementation.

Governance influences breeding priorities by determining the rules according to which conflicting objectives are assessed and how costs and expected benefits are distributed between the organisations involved [41]. Thus, governance does not directly determine individual characteristics, but the procedures, market information, processing requirements, regulatory expectations and social objectives [42]. This requires forward-looking information on market trends, regulatory frameworks, public communication and an intensive transfer of knowledge. New variety characteristics can only be strategically pursued if their subsequent usability and legitimacy can be adequately assessed [43,44]. Thereby, DLB complements both existing governance and innovation system approaches. It coordinates the operational interface between value chain coordination, knowledge integration and breeding decisions.

From this perspective, the exchange of information within and between value chains becomes a central functional condition of DLB. Governance establishes organisational and contractual structures that pool distributed knowledge, reduce uncertainty, equalise asymmetric information thereby securing investment decisions. In legume value chains, which are often characterised by low market depth, high-quality uncertainty and weak coordination, contractual or cooperative governance mechanisms can stabilise expectations regarding qualities, quantities and purchase conditions, reducing the risk of information uncertainty, information asymmetry and enabling breeding orientation [11,41,45]. Governance structures can therefore also support the standard solutions proposed by Akerlof [21]. Moreover, these standard solutions may also be implemented across different sectors, for example through public-private partnerships in plant breeding. Private-public partnerships can be an important instrument for implementing appropriate governance systems and, at the same time, ensure that commercial goals and policy objectives are agreed upon [43]. In turn, this could create a basis for effective collaboration and new business partnerships induced by the governance system [32,45,46]. To make this happen, it's important for the breeding industry to know which players can provide it with this information and data.

3. Data and methods

3.1. Delphi study

We used the Delphi method to investigate the role of the demand-led breeding approach as a possibility to break path dependencies in European legume breeding. A Delphi study can have various objectives and can therefore vary in its design. In its basic form, a Delphi study is a multi-stage, repeated expert or panel survey in which facts about which only incomplete or uncertain knowledge is available are to be assessed [47]. The Delphi method can be used, for example, to produce economic forecasts or in social research, psychology, medicine or educational sciences, or to derive political strategies and as a decision-making tool. Semi-standardised or fully standardised questionnaires are usually used as survey instruments [48]. However, there are also more open, qualitative approaches that can be designed as face-to-face or group

discussions [49]. After each survey wave, the survey results are processed and anonymized. Controlled feedback on these results is then provided to the participants. In the subsequent survey waves, the same topics or questions are addressed. Based on the preliminary results available then, individual participants can submit a new evaluation or statement. They can either align their opinion with the group opinion based on the majority view, or express their own point of view more strongly to influence the overall outcome towards a particular direction. This scheme is carried out until a defined termination criterion is reached. The versatile application options, embedded in an established research design, make the Delphi study method also a popular choice for scientific research in the agricultural and food industry [49–52].

We based our methodological design on Delphi types 3 and 4 according to Häder and Häder, whereas the third type aims to capture the comprehensive opinion and assessment of a defined group of experts to shed light on a diffuse situation or development process [53]. The fourth type aims to build consensus among participants, which can then be used as a basis for political decision-makers, for example. In doing so, we see the application of the DLB approach to European protein value chains as a diffuse issue on which we want to record the assessments of legume breeding experts. At the same time, we aimed to determine the extent to which expert opinions on this topic agree or diverge. Our research questions in this regard are as follows: (1) Can a consensus be found among breeding experts on the assessment of the DLB approach and its potential relevance and implementation in European legume research and breeding? (2) What opportunities and risks are seen in the concept from a breeding perspective, and (3) which stakeholders along the value chain are the most important actors for providing the necessary information, and what are the most important topics on which demands and needs must be communicated?

The experts in the study sample were selected in a targeted manner and not at random. According to Okoli and Pawlowski [54], random populations do not have sufficient expertise in specific areas. The strength of the Delphi study lies in the exchange of ideas between specialists on complex questions. Therefore, the quality of the study largely depends on the group of experts surveyed, who must be selected carefully based on the presumed competence in relation to the research topic. Recommendations in the literature on group size vary between 10 and 30, as representativeness is not determined by quantitative strength, but by level of expertise [54,55]. Regarding the selection of experts for our study, we referred to the consortium of the Horizon Europe research project BELIS and invited 21 individuals who specialise in basic and applied breeding research, as well as market-oriented plant breeding, from 14 European countries. This provided direct access to qualified individuals and thereby reduced the risk of panel mortality across repeated survey rounds. This strategy proved effective, as 19 of the 21 invited experts participated in the first wave and all 19 completed the second and third waves. Such panel stability was particularly important because strong fluctuations in participation between waves would have reduced comparability and would have limited the basis for a statistical analysis of changes in expert assessments over time. Eligibility was restricted to experts with substantial professional experience in legume breeding. Participants qualified if they held a leading role in breeding practice, directed an R&D unit with breeding responsibility, or had conducted independent and relevant scientific research on legume breeding. In institutional terms, the final panel was balanced between experts from private breeding companies and experts from public breeding research institutions or universities with breeding activities. Thus, the panel deliberately covered both applied commercial breeding perspectives and public-sector research perspectives. All invited experts were linked to legume breeding, ensuring thematic consistency with the objective of the study. Recruitment via project affiliation also made it possible to assess the qualifications of the participants in advance and to approach individuals with a comparatively high motivation to contribute to all three rounds. At the same time, this recruitment strategy may entail a risk of network bias or epistemic homogeneity, since the experts were partly connected through a shared project environment. This limitation must be acknowledged, as a common professional context may increase the likelihood of overlapping problem framings and may therefore have influenced the level of consensus observed. However, this trade-off was considered acceptable in light of the requirements of a multi-wave Delphi design. In addition, the underlying project consortium was intentionally composed to reflect diverse socioeconomic, cultural, and geographical contexts across Europe, which broadens the range of breeding environments and institutional experiences represented in the panel. A more detailed participant-level breakdown is not reported in order to preserve confidentiality. Given the small and highly specialised community of experts in European legume breeding, combining institutional and geographic information could allow indirect identification of individual participants. Table 1 therefore reports the number of participants per wave and their geographical distribution in aggregated form. In this research design, the participants are anonymous to each other but not to the person supervising the survey [54].

One additional person joined on top in both the second and third wave. Both were recommended by members of the original panel based on their recognised competence in legume breeding and were invited to restore the initially intended panel size of 21 participants. This could be seen as a limitation of the study, as it departs from the most conventional Delphi format and may have slightly affected strict comparability across waves. The termination criterion, which was that a measurable consensus among the participants must be apparent for the majority of questions, was achieved after three rounds of questioning. The expert group represents both grain legume breeding and forage legume breeding in equal measure. The survey period ran from May to September 2025. The procedure is shown schematically as a flow chart in Fig. 1. After the questions had been worked out, the questionnaire had been developed and the group of experts had been selected, preliminary information was sent out to all participants. Once the questionnaire had been completed, it was pre-tested with the support of the Grenoble Applied Economics Laboratory.

As a data collection tool, we programmed a semi-standardised questionnaire using the paid-for online tool LimeSurvey Professional 6.15.20. The questionnaire consisted of both open and closed questions, which were divided into the four sections A, B, C and D. The A questions related to the country-specific classification of the participants, their professional background and the types of legumes they work with. The B questions related to the first and second research questions concerning attitudes and assessments regarding the DLB approach as applied to European legume breeding and the associated opportunities and risks, as well as the consensus building in this respect. To this end, the B block included open-ended questions that asked participants for a statement or opinion. These were questions such as: ‘From your perspective, how relevant are the needs and expectations of plant breeding ‘customers’ (e.g. processors, retailers, consumers) for the development of new legume varieties?‘. Participants could respond in writing with an unlimited number of characters. On the other hand, closed questions were also asked or statements were provided that could be answered or evaluated using a five-point Likert scale (1 – disagree, 2 – rather disagree, 3 – neither disagree nor agree, 4 – rather agree, 5 – fully agree). These included, for example: ‘It is highly likely that the demand-led breeding approach will become established in European legume breeding in the medium term’. Participants were also asked how familiar they were with the DLB concept, which served to qualify the quality of the expert statements [53]. To this end, the statement ‘I am familiar with the concept or approach of demand-led breeding’ was to be rated on a Likert scale.

The C question block then referred to the question of which stakeholders can provide the most important information about demands and needs regarding plant characteristics, ingredients, etc. for breeding. Nine suggestions were made, such as ‘feed processing companies’, ‘retailers and cooperatives’ or ‘consumers with direct consumption’, which

Table 1
Overview of the countries in which the experts who participated in the study are professionally active and the number per round.

Country		France	Belgium	Italy	Spain	Bulgaria	Germany	Czech Republic	Netherlands	Denmark	Norway	Serbia	Lithuania	Lebanon	Switzerland	Total n
Wave 1	n	1	1	1	3	1	1	2	1	1	1	3	1	1	1	19
Wave 2	n	2	1	1	3	1	1	2	1	1	1	3	1	1	1	20
Wave 3	n	3	1	1	3	1	1	2	1	1	1	3	1	1	1	21

could be rated using the 5-point Likert scale. The D question block was similar, but this time with the question of which topics are relevant in this context. Eleven suggestions were proposed, such as 'primary ingredients or nutritional content (e.g. protein content, fibre, starch, micronutrients)' or 'technological processing properties (e.g. dehulling efficiency, milling properties, cooking time)'. In the first round, additional suggestions were requested for the C and D question blocks, which expanded the lists in the second and third round.

After completion of the first survey wave, data was processed and the second wave was prepared. Feedback from the graphically processed group results, including anonymized participant information on country, etc., was integrated into the online questionnaire for the second wave. This meant that participants had the first-round results at their fingertips when they had to answer the questions for the second time. The written statements were coded and then quantified so that the results could be presented graphically in the form of pie charts with embedded illustrative quotes for each code. The answers to the closed questions were presented in the form of bar charts showing the absolute and relative mentions per category.

The sequence of questions from the first wave was retained in the second wave. In addition to the new answering of the questions, the open questions now enabled an asynchronous discussion of the experts' first-round statements, similar to the procedure used by Sacchi et al. [51]. Six suggestions were added to block C and two to block D. Feedback on the second-round results was provided in the same way as after the first round, during the third round of questioning. In the third round, the previous sequence of questions was retained, with the modification that participants were no longer asked to answer the open-ended questions directly. However, all results of the qualitatively recorded discussion could be commented on. Likewise, all other results could also be freely commented on. In addition, before the C and D question blocks, participants were given the opportunity to express their agreement with the overall assessment of the stakeholders and topics to date. To this end, they were asked to use the Likert scale to rate: 'I fully share the group opinion on the stakeholder groups that should be considered/which information could be helpful for creating targeted product or trait profiles of new varieties'.

Before participating in each round, participants were again informed about the objective, the procedure, data protection and the voluntary nature of participation, and had to confirm that they had taken note of this information. Before the first round of interviews, the overall concept of the study was evaluated by the Ethics Committee of the South Westphalia University of Applied Science. The study description, the submitted consent form and participant information were reviewed and a positive vote was given.

3.2. Evaluation of qualitative and quantitative data and inferential statistics

The qualitative response data from the open questions in round one and two, as well as the comments from all three rounds were analysed by content analysis according to Mayring [56] supported by MAXQDA Analytics Pro 24.11.0. For each of the open questions in the questionnaire, a top-level category was set up. The first-round responses were systematically worked through and, for each question or top-level code, inductive categories were formed on topics or aspects mentioned based on the response material. This resulted in between three and seven subcategories per question. In a second step, the first-round material was then coded using the subcategories created earlier. The individual questionnaires served as the evaluation unit, the entire response or comment was defined as the context unit, and the coding unit consisted of several words with a meaningful connection or individual sentences [56]. The data from the second and third waves were processed in the same way using the existing categories. In all three waves combined, a total of 352 segments were coded. After the third wave, the coded data was analysed across waves based on a qualitative content analysis

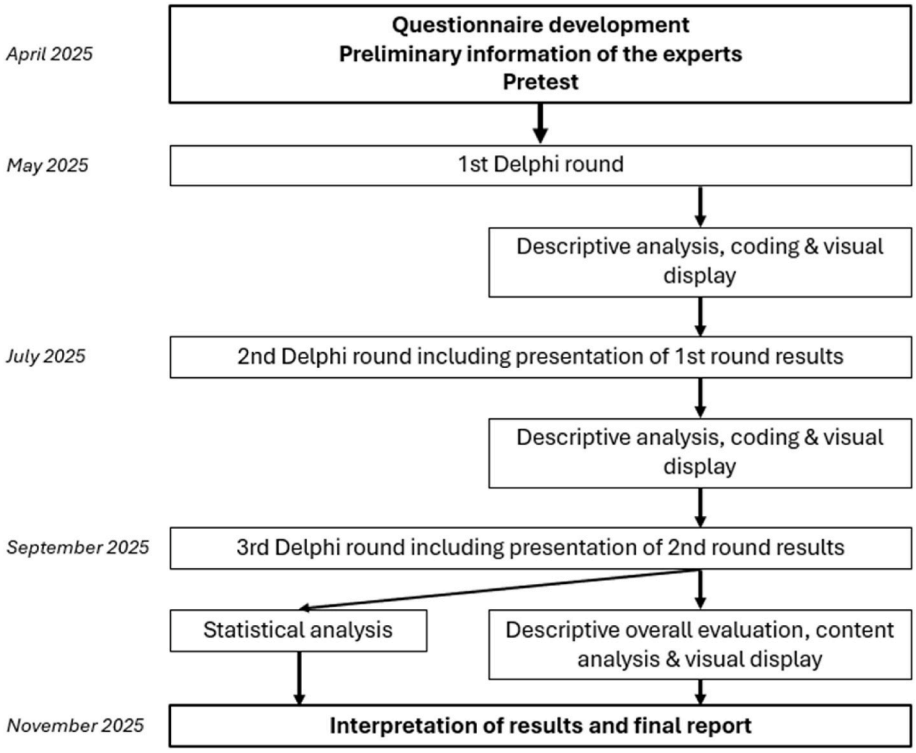


Fig. 1. Schematic flow and procedure of our Delphi study.

according to Mayring [56]. The 'qualitative case and group comparison' function in MAXQDA was used for this purpose. The key findings are presented as descriptive text and additionally supported by illustrative quotations and cross-wave code statistics.

The quantitative data was generated using ratings on a 5-point Likert scale. The Likert scale is a very common scale level in Delphi studies [49,55,57–60]. Since the Likert scale provides ordinal data, the median (*Md*) is used instead of the mean, and the interquartile range (*IQR*) is used as the variation parameter. These were calculated for each question and for each wave using the R Studio programme, R version 4.2.3 [57,61]. The median can be used to descriptively illustrate the middle ratings of the participants and, above all, the changes in ratings across the individual waves. The IQR can then be used to determine how uniform a rating is and, above all, whether the ratings become more uniform over the course of the survey or not. According to von der Gracht [59], a reduction in the variation of the median values can be used as an indicator of the onset of consensus formation. The lower the variation, the higher the group consensus, whereby an IQR <1 on a 5-point scale can be considered an acceptable consensus, as more than 50% of all opinions have fallen on the same point on the scale [59]. In addition, the respective relative proportion of votes for each level per question was determined, which is represented in the form of stacked bars. Using the percentage share (% agreement) of the ratings per level of the scale presented in this way, both agreement or disagreement can be visually represented [57,59].

In addition to the descriptive analysis, we conducted an inferential statistical evaluation of the changes between the survey waves to further validate the interpretations regarding consensus formation. Methodologically, we refer to Sachs and Hedderich [61] and Field [62]. The aim was to examine whether there was a statistically verifiable change in the opinions of the experts that would underline consensus building. Since the requirements of standard distribution and variance homogeneity for parametric tests are not met, only non-parametric test procedures were used [59].

First, a Friedman test was performed as a rank variance analysis for related samples, which checks whether the median ranks of the answers to a question differ significantly across several measurement times (k) ($\alpha = 0.05$). Here, n is the number of participants and R_j is the rank sum of the group. The test statistic Q is (1):

$$Q = \frac{12}{k \cdot n \cdot (k+1)} \sum_{j=1}^{k} R_j^2 - 3n(k+1) \tag{1}$$

The test statistic Q follows with the null hypothesis asymptotically a chi-square distribution with $k-1$ degrees of freedom. A significant p-value indicates that at least two groups differ systematically from each other. Only those participants who responded in all three waves ($n = 19$) were included in this test, as paired comparisons are only permissible on the basis of complete observation series [61].

Subsequently, the individual waves were tested against each other using the paired Wilcoxon signed-rank test as a post-hoc test in order to check in pairs between which survey waves the differences found exist. The Wilcoxon test compares two related samples and checks whether there is a significant shift in the distribution of ranks, which indicates a change in the central tendency between two waves. For each pair $i = 1, \ldots, n$, at first the difference is calculated (2):

$$d_i = x_{i1} - x_{i2} \tag{2}$$

Subsequently, the amounts $|d_i|$ are ranked and differentiated according to >0 and < 0. Then the rank sums (3) and the test statistics can be calculated (4):

$$R_+ = \sum_{i:d_i>0} Rang(|d_i|),\ R_- \sum_{i:d_i<0} Rang(|d_i|) \tag{3}$$

$$R^{\cdot} = min(R_+, R_-) \tag{4}$$

This makes the paired Wilcoxon signed rank test a method that has also been used in other Delphi studies for the statistical evaluation of consensus formation in non-parametric data structures [48,59,63]. For the questions or aspects added in the second wave of the survey, we directly used the post hoc test to compare the second and third waves. Repeating both tests many times for all questions and wave pairs creates

the risk of an α-error accumulation. Therefore, all p-values were corrected according to Holm. The Holm correction controls the family-wise error rate (FWER), ranks the p-values by size and tests them step by step for significance [61].

When interpreting the results regarding the first research question, it is important to always consider indicators together. A significant difference between two different points in time does not necessarily mean that there is consensus at the second point in time, but rather that there has been a shift in opinion. Furthermore, without considering the median, this shift does not reveal anything about the direction of the shift. Conversely, no significant difference on its own does not mean that there is no consensus, but only that the opinion has not changed. It is therefore also necessary to take the descriptive variables into account in order to assess whether, for example, a consensus already existed at the first point in time. To improve the transparency and consistency of the interpretation, consensus was assessed using a combined framework that distinguishes between the level of agreement at a given survey wave and changes in expert judgments across waves. A definition of the consensus criteria applied can be found in Table 2.

Consensus was interpreted symmetrically across the full Likert scale. This means that consensus could occur in the form of shared agreement, shared disagreement, or a shared neutral position, depending on the median response category. The median was therefore used to indicate the substantive direction of the panel's judgment, while the interquartile range was used to assess the degree of dispersion around that position. A consensus was assumed when responses were sufficiently concentrated around a common position on the scale, whereas strong consensus referred to particularly tight clustering. Statistical tests were used to identify whether judgments changed significantly across waves and were not interpreted as direct evidence of consensus. In this way, the analysis distinguishes between the substantive position of the panel, the degree of convergence at a given wave, and the dynamic process of convergence over time.

When interpreting the results regarding research questions 2 and 3, a ranking of stakeholders or topics should be created based on the following order of indicators: Here, the higher the median, the lower the IQR and the greater the percentage of responses in categories 5 and 4, the higher the priority. The presence of a consensus or strong consensus has no direct influence on the position in the ranking. The statistical analysis of convergence serves here only as an indicator of whether there has been a change in the group's assessment across the three waves.

The results of the descriptive and statistical analysis are presented together in an integrative figure for each block of questions. The p-values of the Friedman test (p_{Fr}) are plotted for each question and, if there is a significant change, the p-values of the paired Wilcoxon signed-rank tests (p_W) are also plotted for each wave comparison (1/2, 2/3, 1/3). All test results can be found in Appendix 1.

Table 2
Operational criteria used to distinguish consensus, strong consensus, and consensus formation in the analysis.

Category	Definition	Operational criteria
Strong consensus	A highly pronounced and tightly clustered agreement among experts on a given item at a specific wave.	Median indicates a common substantive position on the scale and very high concentration of responses on the median category. Median 1–5 IQR <1
Consensus	Substantive agreement among experts on a given item at a specific survey wave, combined with limited dispersion of responses.	Median indicates a common position on the scale. Median 1–5 IQR = 1
Consensus formation/ convergence	A process in which the expert judgements shift over the course of the survey waves, without full consensus necessarily being reached.	Increasing concentration of responses around a common scale position and statistically significant differences across waves in the paired Wilcoxon signed-rank tests.

4. Results

4.1. Assessment and evaluation of the DLB approach and forecast

In the following chapters, we present the results of the expert group's qualitative assessments of the relevance of the DLB approach and the consequences of its targeted implementation. In addition, the results of the quantitative, closed questions and the statistics are presented in figures. Fig. 2 refers to the experts' general opinion with regard to the DLB approach. In addition, Fig. 3 shows the results regarding which stakeholders from the need cluster provide the most important information for the development of variety profiles and which actors are the most relevant for cooperative collaboration with breeding. Fig. 4 then illustrates how expert assessments have developed with regard to the thematic areas in which information should be exchanged with the need cluster.

Fig. 2 shows that just under 60% of participants fully agreed that they were familiar with the concept at the time of the last wave. Compared to the first wave, there was a significant shift in opinion towards stronger agreement in the second and third waves, as $p_{Fr} = 0.014$, $p_W = 0.025$ (wave 1/2) and $p_W = 0.036$ (wave 1/3). This suggests that the participants engaged more intensively with the DLB concept during the survey period. The results also show that there is a strong consensus that breeding priorities should generally be adjusted depending on the final use of the legumes. A significant shift towards 'fully agree' when comparing the first wave with the second and third indicates a consensus formation.

This result is in line with the assessments of the experts regarding the importance of knowing the expectations of the need cluster. The code statistics for this question can be found in Table 3. According to the expert group, downstream needs are certainly considered to be of high importance, which becomes evident for example in the following statements: „*Highly relevant — customer needs to guide traits like taste, nutrition, shelf life, and processing suitability*." Or "[…] *the needs and expectations of the customers are very important from a practical point of view. The traits that are most valued by them give the main directions of the basic research and breeding programs that are followed when a new variety is developed*."

The expert opinions also reveal various areas in which downstream stakeholder needs play a central role. First and foremost among these is the ongoing definition, testing and validation of breeding profiles, but also feedback on current market demand and the establishment of Value for Cultivation and Use (VCU) criteria for the registration of a variety. Furthermore, knowledge of the various needs enables the targeted orientation of legume breeding for special markets or specific market segments. This refers to the definition of speciality raw materials as opposed to commodity raw materials. However, one problem that reduces the actual, true influence of the downstream chain is that farmers are so far paid only according to quantity and only to a very limited extent according to quality. As a result, the supply or production of raw materials with very specific qualities fails due to the economically motivated decision of the agricultural sector to focus on high-yield varieties: „*The farmer is rarely paid for the quality of its production. The driver of its income is the quantity that is sold (i.e yield)*." Since breeding itself is dependent on the acreage of the varieties for economic reasons, this reduces the importance of special requirements. That also means the importance of the needs of the downstream chain is somehow limited. In this context, too, a kind of deadlocked cycle or lock-in can be identified, which can only be overcome by the downstream stakeholders' willingness to pay for advanced qualities.

Some experts also argue that customer expectations are somewhat more or less relevant, but breeding programmes often follow highly complex objectives that require prioritisation to address conflicting

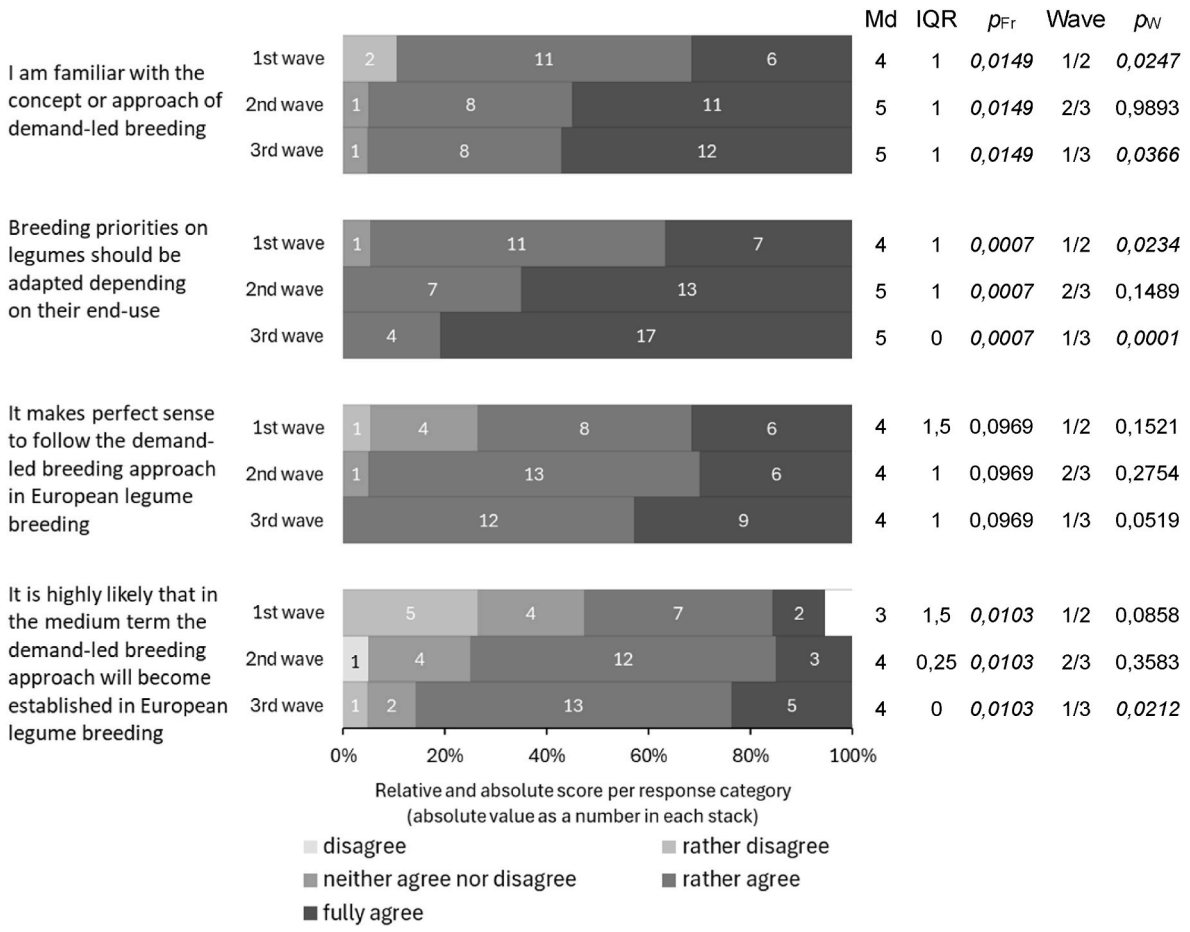


Fig. 2. Display of all responses in relative and absolute numbers as stacked bars per wave and closed question regarding the DLB assessment (B question block), including statistical analysis per question.

Table 3
Cross-wave code statistics (sum of codes from all three waves) on the relevance of customer needs.

From your perspective, how relevant are needs and expectations of the customers of plant breeding?		
	Encodings n	Share%
Very relevant	21	72,4
More or less relevant	7	24,1
Not relevant	1	3,5
Total	29	100

goals. But these goals are often not understood by downstream sectors. These include, for example, the various plant reactions to the environment or often undesirable correlations of characteristics. In a few cases, it is also stated that the downstream chain is of significantly less importance for forage legumes. Unlike grain legumes which may undergo multi-stage processing, they are used almost exclusively as a commodity in animal feed. At the same time, however, it is also mentioned that even in the case of forage legumes, consumers of animals fed with these plants should have an indirect influence on breeding. For example with regard to sustainable feed production and animal welfare. Only one expert reports, contrary to the group opinion, that breeding objectives today are determined solely by breeders, unaffected by influences from the value chain.

One aspect that has not been considered so far, but which was also mentioned in the context of this question, is that even if all needs could be met equally through plant breeding, there are still other desirable goals that are not covered. This is because they are not in demand on the market. Hence, the public authorities are brought into play as member of the plant breeding need cluster, demanding that breeding also take societal goals such as environmental protection into account.

However, explicit integration of the need clusters expectations is associated with a series of advantages that can be assigned to several main categories. These can be found in the code statistics in Table 4. The most frequently reported opportunity offered by DLB is the stronger alignment of breeding goals with market demand. Satisfying previously unmet needs with products derived from adapted varieties, supplies new or expanded value chains, which in turn generates retroactive financial added value for the breeding sector: *„Greater alignement to specific needs should correspond to an extra commercial value assigned by the market to the*

Table 4
Cross-wave code statistics (sum of codes from all three waves) on the opportunities of applying DLB.

What are, in your opinion, the main opportunities of applying a demand-led breeding approach to legumes?		
	Encodings n	Share %
Orientation towards Market Demand	11	30,6
Stakeholder Alignment and promotion of Cooperation	6	16,7
Orientation towards Market Size/Relevance	6	16,7
Improving Seed Access and Quality	4	11,1
Shifting the Focus to Quality Traits	4	11,1
Contributing to Economic Growth	4	11,1
Increasing Sustainability	1	2,8
Total	36	100

product of the variety.“

In this regard, experts also expect a significant shift in breeding priorities towards quality parameters. This should increase the willingness to pay of those who actually demand these same quality characteristics. In addition, the potential expansion of intra-value chain-specific cooperation, stakeholder networking or the establishment of exclusive value chains is described as an opportunity. However, it is also emphasised that DLB does not necessarily have to take every demand into account. The concept is also suitable for showing breeders the most relevant markets to which it is worth responding. For example, due to promising future market potential or rapidly developing market growth. The interaction and mutual influence of the aspects described can ultimately help to increase overall value creation and contribute to overall economic growth. This could also lead to improved seed availability, as private seed companies could become increasingly interested in the legume sector.

On the other hand, however, there are also some barriers or risks that need to be borne in mind from the perspective of legume breeding. The respective categories are listed in Table 5. One of the biggest hurdles are the long time loops required for the development of new varieties using traditional breeding methods. This means that a trait that is in demand today may only be achieved in a new variety many years later: *„Consumers and processors need to have patience, as breeding often takes more than 10 years.”* By that time, the market and thus also the requirements for certain characteristics may have further evolved or changed. In this case, breeding outputs will lag behind demand. In addition, increasing administrative and regulatory hurdles are expected. Particularly regarding the use of legumes in ingredient production and in the approval of legume products for human consumption. These may also vary from country to country, which could make the overall process of variety registration more challenging and time-consuming. This in turn leads back to the dilemma that legume breeding programmes are often not economically viable and difficult to finance. On the one hand, this is already slowing down the natural establishment of demand-oriented breeding. Even if breeders theoretically had knowledge of all specific requirements and needs, it is not the will that is lacking, but the money to fulfil them. On the other hand, there is a risk that the extra work put into developing new varieties won't lead to extra income: *„There is no guarantee that a new variety will generate sufficient profit, even if the needs of all downstream stakeholders are carefully considered. No strategy can ensure the high profitability of a new variety, regardless of how meticulously it is developed.”*

The breeding industry would have to make up-front financial investments for new innovations and additional requirements. This is hardly feasible given the economic bottlenecks that already exist. For the breeding industry, this is another indicator of the lock-in scenario mentioned above.

Added to this is the concern that breeding goals will become so complicated that they will no longer be manageable, because: (1) Too many problems will arise due to negatively correlated traits. (2) The focus on the truly relevant breeding goals will become blurred: *„Sometimes consumers care about things that are a bit “nonsense”. Should the breeders pay a lot of attention to this or not? If it is only “fashion” that does not really matter?”* In addition, some experts complain about a lack of support and resources for legume breeding programmes. Especially when there is no lasting exchange with downstream sectors and certain demands are only expressed indirectly rather than being communicated precisely.

This leads to the question of how breeding experts are assessing the exchange of information with the need cluster. This is quantified in Table 6. It shows that the majority of experts stated that they did not receive enough or comprehensive information from the value chain: *„We receive some feedbacks but this is fragmented. It is necessary to have a more organized communication to align breeding efforts with the real needs”*. In this context, the desire for regulated and more frequent networking is expressed repeatedly. The quality and quantity of feedback decreases with increasing distance in the value chain. The exchange of information is functioning relatively well with respect to the agricultural sector. But it is all the more fragmented when it comes to highly processed foods and social needs such as climate protection and landscape aesthetics. It is noticeable that the statements that can be assigned to the category ‘Enough feedback’ predominantly refer to forage legumes. In contrast to the area of grain legumes, the information chains for forage legumes appear to be more direct. Experts report good relationships with farmers, associations or seed companies in some cases. However, some participants also argued that the market should actually be the information interface between breeding and agriculture and the rest of the chain. A functioning market should be able to adequately reflect downstream requirements, making stronger stakeholder networking among themselves somewhat unnecessary.

Looking back at the experts' assessments in Fig. 2, two key findings can be noted: At the time of the last survey, the experts agreed that it made rather good sense to adopt the DLB concept. In this regard, a consensus could be observed. The second key finding is that, with regard to future prognosis, the experts predominantly rather believe that the DLB concept will become established in Europe in the medium term despite the obstacles described. This is reflected by the consensus in favour of this statement. In addition, the statistical analysis revealed that there was a convergence in opinion between the first and third waves of the survey.

4.2. Prioritising stakeholder groups for information transfer

In the following, we discuss the results regarding which stakeholder groups provide the most important information for the development of variety profiles, as shown in Fig. 3. These are also the most relevant for cooperative collaboration with breeding. The downstream stakeholders who received the highest agreement ratings were feed processing companies and research and application institutions for animal nutrition ($Md = 5$, $IQR = 1$). In relation to the area of animal nutrition, it can be noted that consensus was being reached. These areas are followed by the food processing sectors while Farmers as producers and livestock farmers as users of legumes are placed fifth and sixth. The ranking is

Table 5
Cross-wave code statistics (sum of codes from all three waves) on the risks of applying DLB.

What do you see as the main barriers and risks of implementing demand-led breeding in the European context?		
	Encodings n	Share %
Funding and profitability	9	25,0
Timing challenges	9	25,0
Regulatory hurdles	5	13,9
Complexity of breeding objectives	4	11,1
Balancing societal and consumer needs	4	11,1
Insufficient support for legume breeders	3	8,3
Other	2	5,6
Total	36	100

Table 6
Cross-wave code statistics (sum of codes from all three waves) on the exchange of information.

What is your opinion on the statement that breeders in Europe currently receive sufficient feedback from downstream actors/customers?		
	Encodings n	Share %
Lack of comprehensive feedback	17	65,4
Enough feedback	7	26,9
Market responsiveness	2	7,7
Total	26	100

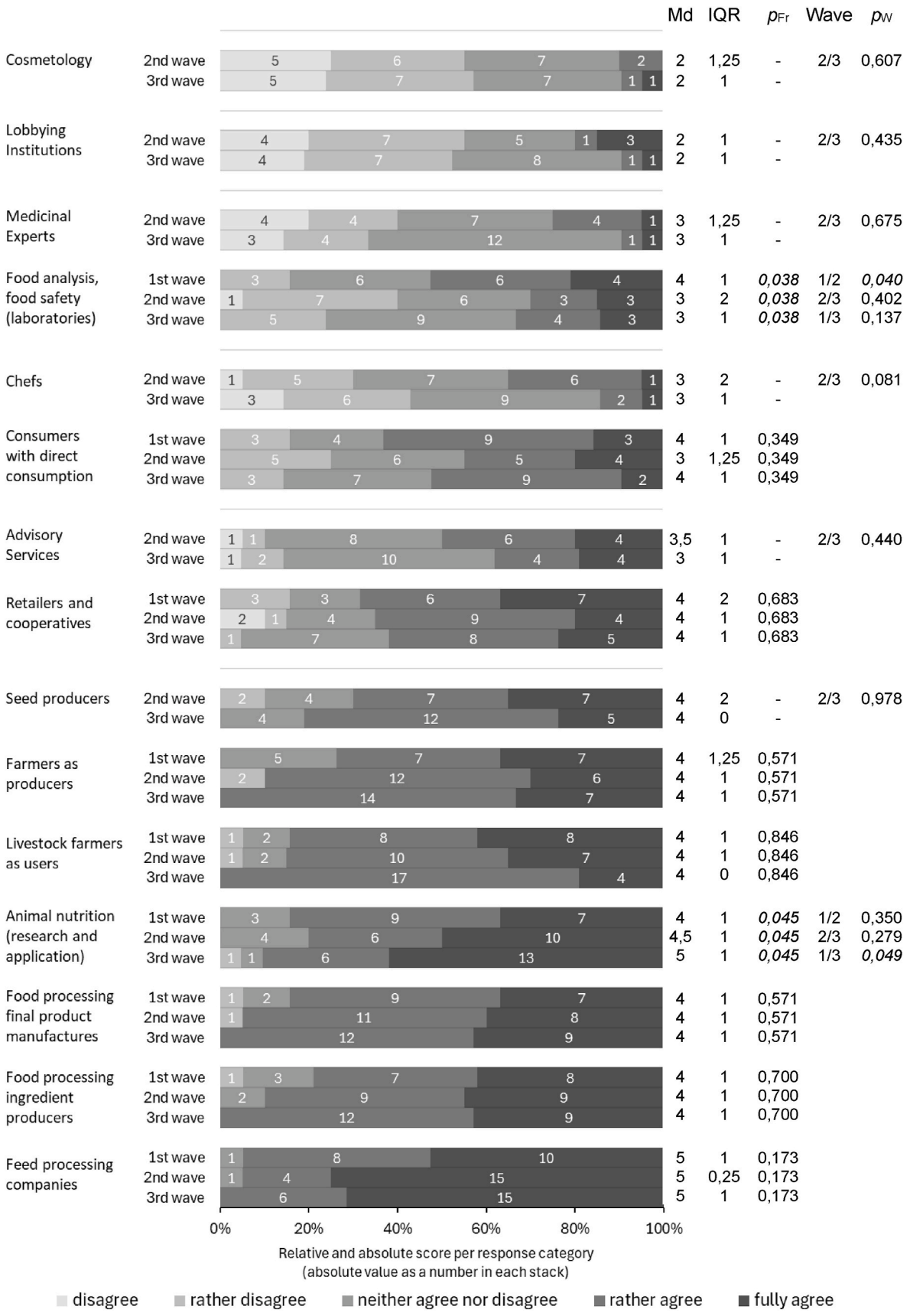


Fig. 3. Display of all responses in relative and absolute figures as stacked bars per wave and closed question regarding stakeholder assessment (C question block), including statistical analysis per question.

then followed by seed producers, traders and cooperatives, and consumers with direct consumption. The respondents have demonstrated a rather clear rejection of lobbying institutions and cosmetologists ($Md = 2$). In all three cases, this was reflected with a median of 2. Also, there is a consensus in favour of rejection. In order to record not only the agreement or disagreement of individual stakeholders, but also in relation to the agreement or disagreement of the prioritisation, an evaluation based on the second rounds' results of the present rankings should be carried out in the final wave. The median rating was level 4 (rather agree) with an $IQR = 1$. It was observed that all responses were in the agree levels 4 (52%) and 5 (48%). Consequently, it can be deduced that the expert group is, in general, satisfied with the ranking.

4.3. Prioritisation of topics relating to the information transfer

We also present the expert groups' assessment of specific content

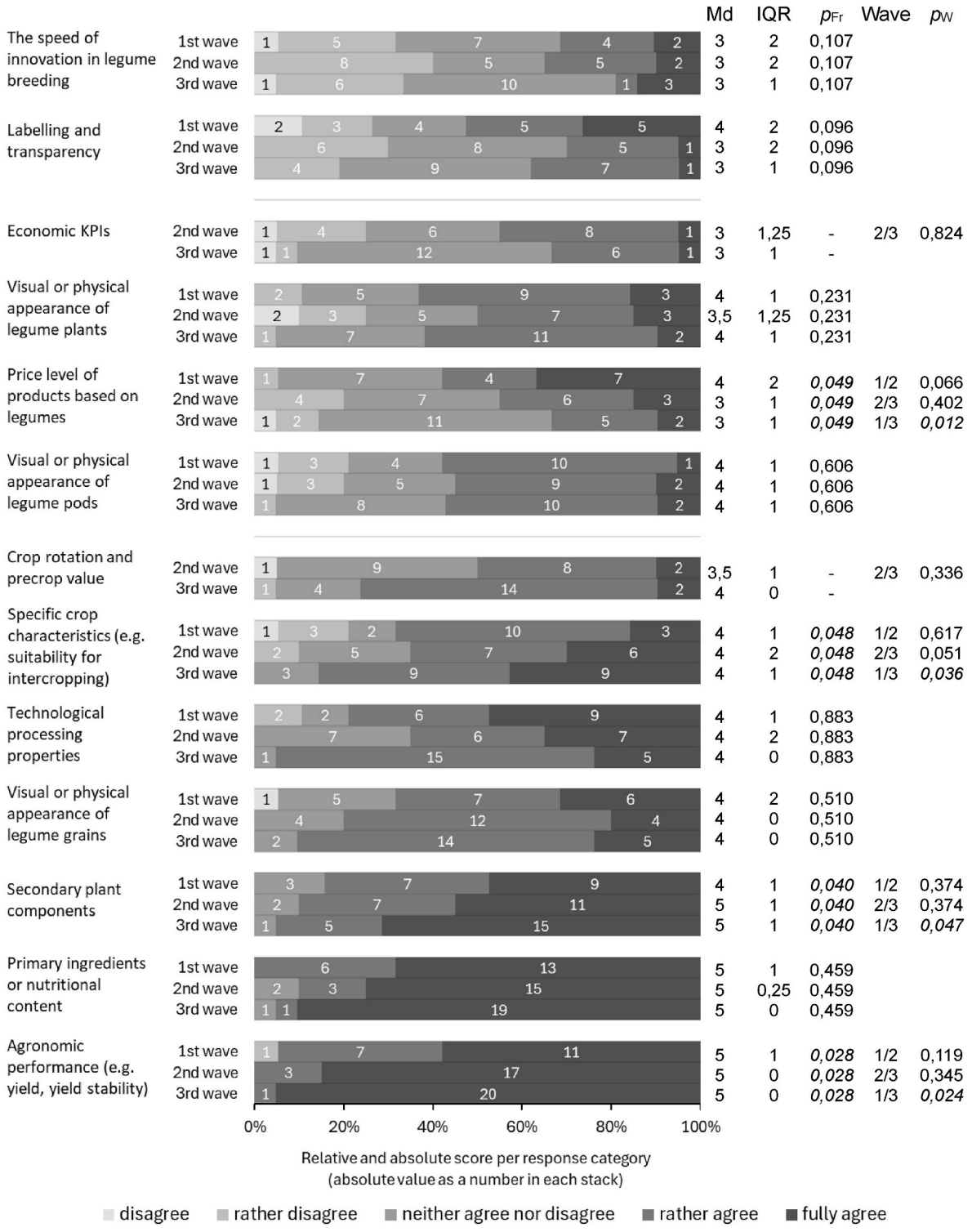


Fig. 4. Display of all responses in relative and absolute figures as stacked bars per wave and closed question regarding the topic evaluation (D question block), including statistical analysis per question.

areas as a ranking, as shown in Fig. 4. The area in which there was the highest level of agreement is agronomic performance. This includes aspects such as yield, yield stability, or resistance to abiotic and biotic stress. In addition, a significant difference between the first and third wave, indicates that there has been a further convergence in the strong consensus over time. Secondly, the primary ingredients or nutritional content is considered. Here, protein, starch and fibre content being given as exemplary cases. In third place is the area of secondary plant compounds. In addition, a convergence resulting from an increase in agreement has led to the area of specific crop characteristics being placed at position five. Whereas, unlike in the case of the visual or physical appearance of legume grains, processing properties, and crop rotation and the precrop-value, there is no strong consensus on this point. This is followed by the aspects of technological processing properties (e.g. dehulling efficiency, milling properties or cooking time) and visual or physical appearance of legume grains (e.g. colour, surface or grain size). The subjects with the lowest ranking in the prioritisation correspond to economic key performance indicators (KPIs), the price levels of products based on legumes, labelling and transparency, and the speed of innovation in legume breeding. The median rating of the entire group on the question of whether they are satisfied with the ranking of the topics corresponds to level 4, 'rather agree', with an *IQR* of 1.

5. Discussion

5.1. Delphi study results on the potential of DLB in relation to existing system vulnerabilities

The research methodologically guided by the Delphi study is based on the assumption that we see the concept of demand-led breeding (DLB) as a paradigm that is worth examining in greater depth. We want to examine whether the concept has structural, synergistic added value for legume breeding, but also for the European protein sector as a design principle for a governance orientated structure for value chains. After three rounds with almost no change in the participant group, the group opinion achieved is generally extremely reliable [54]. The iterative open questioning enabled exchange and response, or an indirect discussion process, which would not have been possible with a one-off questionnaire.

However, there are also some limitations of the Delphi method to bear in mind [55]. According to Franklin and Hart, these begin as early as the questionnaire design stage [64]. This is based on the researcher's knowledge and a review of the literature. Consequently, the study depends on the ability of those designing the study to identify the key issues and contextual factors accurately. To counteract this limitation, the questionnaire was pre-tested by social science researchers with extensive expertise in the subject area. Although the approach is well suited to structuring expert judgement on complex and forward-looking topics, it remains based on qualitative interpretation rather than on direct empirical measurement of actual behaviour, market outcomes, or breeding decisions in practice. The results should therefore be understood as a systematic assessment of expert perspectives, not as empirical proof of how demand-led breeding processes operate in real-world settings. Furthermore, the aim of reaching consensus hinders extreme but innovative ideas. Potential groupthink effects and the limitation of desirability bias must also be addressed. It includes the risk that a specialised expert community with a common background may answer questions based on their idealised vision rather than their realistic evaluation [65]. Finally, the findings are not statistically generalisable beyond the expert community studied. Their value lies instead in identifying plausible priorities, areas of convergence, and relevant framework conditions that can further support empirical research [66]. Despite the diversity of professional and institutional backgrounds, it cannot be ruled out that the perceptions and assessments of the participating experts are more similar than would have been the case with a broader or differently composed group of experts. This is due to possible epistemic homogeneity. It is also likely that experts with fundamentally different views or a more critical attitude towards the DLB concept would have been less likely to participate in a multi-wave Delphi study. Greater diversity in the panel would have broadened the range of possible perspectives and thus potentially also increased the generalisability of the results. At the same time, it is not possible to reliably assess how experts who were not included would have responded or whether they would have arrived at significantly different assessments. Future studies should examine the extent to which the assessments and consensus patterns identified here can also be confirmed in differently composed panels or in broader empirical studies.

In the following, the research questions will first be discussed based on the results of the study. Subsequently, logical assumptions will be made from the aspects addressed regarding possible developments if attempts are made to implement DLB in a governance-oriented manner. In this regard, new hypotheses are also put forward that illuminate DLB in the larger context of an entire value chain. Throughout this section, statements explicitly derived from the Delphi results are distinguished from broader interpretative implications and literature-based reflections, which are used to contextualise the empirical findings and to discuss their wider relevance.

With regard to the research question concerning the consensus on the assessment and relevance of DLB, we derive the following from the results: A strong consensus was reached on the question of whether breeding priorities should be made dependent on the end use of legumes. A strong consensus was also reached on the question of whether DLB will become established in the medium term. A consensus was reached on the question of how much sense it makes to pursue DLB and how familiar the experts are with the concept. In this regard, we make the following interpretation based on the data and with reference to the theoretical perspective of Lammerts van Bueren et al.: The strong consensus among experts that DLB will tend to establish itself in Europe in the medium term indicates that the current system will have to be adapted accordingly. Lammerts van Bueren et al. term this a shared sense of urgency to change the overarching goals of plant breeding and the entire system [35]. In this regard, the study findings suggest in that the breeding system is possibly becoming more open to greater integration of downstream impulses. Furthermore, the results suggest that the expert panel in question not only agrees with the approach itself but also accepts a potential shift in the legitimacy of breeding objectives. This acceptance is necessary to enable the breeding sector to accord greater importance to downstream factors.

In relation to the research question regarding which stakeholders from the need cluster are the most important for obtaining information, we can state the following based on the results: From a breeding perspective, the main focus is on the animal feed industry and animal nutrition. This can be explained on the basis of literature which shows that, in quantitative and economic terms, legume use in Europe is predominantly concentrated in animal nutrition [67,68]. In addition, the European feed market is more established, so it can be assumed that breeders are already familiar with many of the requirements. This could also lead to a lower risk of undesirable developments or incorrect prioritisation of breeding goals [69]. However, the processing industry in terms of product manufacturing for human nutrition follows in the ranking, most likely because this is seen as a relevant market for the future. Based on literature, a trend can already be observed in the demand for legume protein for direct human consumption, and the suitability and importance of legumes in this context is well known [67,70]. This is supported by scientific studies on the significantly higher sustainability and environmental compatibility of meat alternatives made from legume protein [71]. The agricultural sector follows, both as a producer and as a user or consumer of grain and forage legumes. Agriculture representing the most direct and classic user group that demands the services of plant breeding. We therefore derive the hypothesis that the identification of the relevant stakeholders for the implementation of

DLB is a fundamental prerequisite for the establishment of cooperation [72,73]. We conclude that legume breeders could therefore make immediate use of the information regarding which stakeholders have the highest priority in this regard. In total the Delphi results also provide insight into who the key players are in multi-stakeholder collaborations within the framework of breeding innovation systems [25]. This reveals exactly where the key connection points lie within the value chain.

Regarding the topics, the results reveal that the top priority remains the yield or the agronomic performance of the varieties. With the inclusion of literature-related perspectives, it is the most important factor in variety choices and thus also in generating income from breeding [16,74]. At the same time, according to Sanderson et al. yields are also important for processing companies in order to reduce procurement risks and guarantee supply [75]. However, even when considering the focus on DLB, crop yield remains highly relevant to increase and adjust the total production of raw materials in relation to European consumption and demand [69,76]. This is followed by the primary and secondary components that determine both the feed and nutritional value of the plant material [77,78]. This seems logical, given that these have been identified as the most important communication partners. For legume breeding, this study results mean that even if breeding were to focus more strongly on DLB, the agronomic performance of the crops would remain a relevant breeding objective. This implies that the implementation of DLB does not necessarily require entirely new genetic variation, and that a DLB programme does not have to start with new crosses. DLB can also be pursued using existing lines, for example through adjustments to the selection process. Assefa et al. describe the application of DLB in this context as the fine-tuning of formal breeding programmes [19]. Therefore, DLB does not represent a replacement for existing techno-procedural methods to defining breeding goals, but rather prompts a recalibration or readjustment of processes of how breeding goals are determined.

With regard to the research question concerning the opportunities and risks that DLB can bring, the following can be stated: Based on the study results, it can be interpreted that the DLB concept could induce a synergistic effect that influences the legume value chain and thus also the feed and food system. Cooperative networking between the stakeholders involved to exchange information on existing needs with regard to traits of legumes that can be influenced by breeding makes it possible to take implicit demands into account. And also to design genetic material in line with specific objectives. In this way, DLB could become a driving force within the breeding innovation system in potentially or partly unlocking existing lock-in structures. The development of genetic material and varieties that can meet existing or previously unmet demand could increase the value of the raw materials produced by agriculture and the willingness to pay for these goods [79]. This could make these varieties more attractive to agriculture, as the focus would no longer be solely on maximum yield but on demand-specific quality characteristics. On the one hand, this may increase the profitability of legume cultivation even on small acreage through higher prices for specific qualities. On the other hand this may increase the attractiveness of legume cultivation, which could lead to an increase in acreage [17]. Drawn from relevant literature, both potential developments would benefit legume breeding. Either through higher licence fees per seed unit or through higher licence fees due to higher sales rates of corresponding varieties [14]. In this regard, a hypothesis can also be put forward that DLB potentially has a strategic long-term influence on foreign trade. If domestic grain legumes were to gain comparative advantages, soybean import volumes could be reduced [46,80]. This could reduce import dependency or the so-called protein gap, thereby addressing key issues in European self-sufficiency [69].

DLB is associated with several risks and barriers. DLB processes are currently unlikely to develop or emerge on their own but must be specifically induced. In addition, it can be deduced that, the comprehensive problems described, such as the time lag in breeding, and the administrative hurdles, reinforce each other. New investments cannot be realised if the existing breeding programmes are not economically viable. We described a self-reinforcing cycle between breeding and downstream sectors that limits the importance of the needs of the need cluster. It is also important to highlight the view held by breeders that there is less targeted exchange of information with downstream stakeholders than would be desirable. In this regard, there seems to be a lack of suitable communication structures at the interface between breeding and downstream food system stakeholders, right through to the consumer [81]. The findings suggest that there seem to be a lack of formalised coordination mechanisms. This underscores the fact that the implementation of DLB is dependent on the existence of appropriate governance structures [5,28]. These findings and obstacles contradict the experts' prediction that DLB could become established in the medium term. As described, the DLB concept may have the theoretical potential to partially offset the barriers identified on the breeding side through the advantages that implementation could bring. However, because these barriers exist, DLB cannot become more established. In a metaphorical sense, the complex system somehow lacks a catalyst. However, there are already a few individual examples where a specifically induced DLB process has been initiated within the framework of a project. These include the AlinOVeg cooperation project in France. In this project, among others, the breeder Agri Obtentions is working with the protein processor Roquette and the milk processor Eurial to develop pea varieties that have no off-flavour and are particularly suitable to produce plant-based milk substitutes [82].

In total the empirical findings show that the challenge lies in the institutionally facilitated integration of those stakeholders and information flows that are necessary to translate market-driven requirements into prioritised breeding objectives. Our analysis indicates the need for governance mechanisms that mediate between the value chain, knowledge integration and defining objectives. The findings thus contribute not only to assessing the feasibility of DLB, but also to a better understanding of the conditions under which breeding innovation systems in the legume sector can become aligned with demand-driven impulses.

5.2. Vertical development partnerships as a solution for the implementation of DLB and implications

In order to enable this activation of DLB processes, we could imagine a model of an at least temporarily exclusive vertical cooperation system. To further discuss the impact of DLB within the context of the value chain this is briefly illustrated below based on the theoretical framework of a multi-partner strategic alliance [83]: The focus would be on development partnerships between the breeding sector and its need cluster within the framework of direct cooperation between the breeding sector and a partner in the downstream chain. In addition, it includes the integration of agriculture within the framework of contract farming models. The partner from the downstream chain could, for example, be a manufacturer of products for the food sector that has specific requirements in terms of water vapour permeability, transparency and solubility of the protein [84]. Together, they can discuss the extent to which these properties can be modified through breeding. The development of needs-oriented genetic material or varieties within the framework of such a development partnership would not be carried out for the open market. The newly bred lines would remain within the closed structure and would not have to undergo formal variety registration process. Instead, they would be produced under controlled conditions by contractually bound farmers and then be taken over by contractual collection points and passed on exclusively to the respective development partner (e.g. processing or utilisation company). Within the framework of such a cooperation, the breeding organisation could receive contractual remuneration or funding for the development of order-specific trait profiles. This would enable the breeding organisation to operate on a secure financial basis and would mean that it would no longer have to make investments in innovation development upfront. At the same time, guaranteed purchase conditions and prices would

provide farmers with an economic incentive to participate. The development partner of the breeding programme would in turn may optimise processes, improve quality or enhance market positioning through targeted raw material specifications. Thereby it would be possible to amortise the additional costs incurred [79]. Agreements on quality, quantities, prices and cultivation conditions are made between the partners involved. However, such a structure would have a sensitive impact on the breeders' exemption as an established principle [85,86]. It is therefore also necessary to discuss the extent to which this might result in potential varieties not being registered and thus not being available for further innovation by all breeders.

The above-mentioned option of development partnerships goes beyond the findings of the Delphi study. It should therefore be understood as one possible logical deduction of what a scenario for the implementation of DLB might look like. In the following, we would like to present some assumptions regarding the potential impact such a scenario could have on the entire food system or the value chain. These are hypotheses and not empirically proven findings. Such a coordinated model could avoid the fragmentation of existing market structures, restructure incentive mechanisms within the value chain and improve predictability along all stages of the food system. This is because the resulting product could have unique selling propositions that would differentiate it from previous goods. Meynard et al. [73] refer to this as breaking the dependence on commodity markets. In particular, contract farming of appropriate breeding lines or varieties could enable secure, stable and functional trade relations with reduced transaction costs and significantly reduced risk [87–89]. Regardless of dealer distribution and possible periods of non-trade [11,90]. Furthermore, the elimination of formal certification and variety registration procedures could contribute to administrative simplification and shorter breeding cycles, enabling a much quicker response to changing needs. This construct can be described as a vertical strategic alliance within the framework of cooperative development partnerships [83,91,92]. Strategic alliances are an established framework for collaborative cooperation between companies to increase value creation and productivity. In the agricultural context, too, the structure is familiar, for example in the context of producer cooperatives. The economic characteristics of strategic alliances can be transferred to the model of exclusive development partnerships [93–95]. This model system also enables the three main conditions identified by Meynard et al. for overcoming the legume sector lock-in complex simultaneously [73]. For instance, the positioning of products with specific characteristics can be improved. Furthermore, there is coordinated cooperation between stakeholders, which enables the fair distribution of the added value achieved. Moreover, it is essentially a combination of genetic, agronomic and technical innovation. The model of vertical development partnerships could thus serve as a structural framework for establishing DLB processes for private breeding actors.

Against this backdrop, we conclude with three key implications for agricultural research and for the legume breeding industry itself:

(1) It was shown that information exchange between (grain) legume breeding and the need cluster could be improved. Nevertheless, for DLB to be successful, it is essential that the relevant stakeholders are aware of one another, come together, and share information about their requirements. The same applies to a general governance-oriented transformation of the legume sector against the backdrop of public food security objectives [41,73]. We therefore recommend that research should focus on ways of how a functional information infrastructure between breeding and the downstream chain could look like and how to establish and maintain it. According to Mawois et al. [81], peer networking and, according to Voisin et al. [96], approaches within the framework of an eco-innovation approach in conjunction with specialised intra-value chain-specific workshops can be mentioned as possible starting points for networking. This could also be helpful in establishing exclusive vertical development partnerships. However, the hypotheses put forward regarding this alliance-like model still need to be investigated further, as there are very few studies on this topic, particularly in the context of legumes.

(2) The feed industry and animal nutrition have been identified as the most important partners in the cluster of demand groups that require the outputs of legume breeding. Even without exclusive development partnerships, the feed industry is a 'secure' cornerstone for agriculture and thus also for breeding. Even if European livestock populations were to decline, there is still potential to replace the current share of imported feed soy with domestically grown legumes [46,53,69,97]. From the perspective of legume breeding, our recommendation is therefore to even intensify the relationship with the feed sector, expand communication and knowledge transfer, and seek cooperative partnerships in this area.

(3) In the introduction, we described how the literature refers to a paradigm shift in breeding in relation to the DLB approach. Our study could demonstrate that even when pursuing the DLB approach, traditional breeding objectives such as agronomic performance remain the top priority. However, this is not in conflict with a demand-oriented focus. Breeding objectives relating to the food sector, such as primary and secondary components, follow closely behind. Our implication from this is that DLB should not be understood as a radical restructuring of breeding governance. Instead, it should be seen as a new guiding principle that induces smooth improvements whilst taking existing needs into account within existing breeding programmes.

6. Conclusion

In conclusion, we can verify the suitability of the Delphi study's research design for investigating our research questions, apart from some limitations. In doing so, we were able to increase a consensus among breeding experts in several respects regarding the assessment of the demand-led breeding approach and evaluate the opportunities and risks seen in the approach from a breeding perspective. These primarily include the potential increase in revenue for the breeding industry due to the correlation between demand for raw material, demand for varieties and licence income. Nonetheless the risk of missing a demand in time and the uncertainty of the success of a specific variety innovation must be born in mind. At the same time, we have been able to determine that stakeholders from the areas of feed production and animal nutrition, as well as food production and processing, are the key points of contact. The study's particular contribution thus lies in placing the DLB approach within the context of legume breeding for European conditions and in identifying it as a mechanism within breeding innovation systems while showcasing breeding expert's opinions on this issue.

We were also able to clearly demonstrate that the legume breeding sector is aware of the advantages of greater integration of implied downstream needs. Under the assumptions of a perfect market with scarcity prices and no niche existence for domestic grain legumes, the DLB approach would probably be a natural or self-regulating process. However, as these assumptions are not given, DLB remains an idealistic model for legumes. We have therefore put forward the hypothesis that DLB may first need to be followed up in the context of exclusive vertical development partnerships to avoid the existing hurdles. However, the effects on the breeders' exemption need to be assessed. The overall situation is anything but trivial, as the scope of the influence of plant breeding and the intertwined relationships with the food system are difficult to grasp accurately. Nevertheless, based on the results and interpretations, we were able to translate the collected expert knowledge into implications for the agricultural system. These involve the strategic research into improving the exchange of information, the targeted close

cooperation between legume breeding and the feed sector as well as the understanding of DLB as a fine-tuning of existing breeding programmes.

CRediT authorship contribution statement

Lars Wernze: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Michaela Schmitz:** Supervision, Writing – review & editing. **Marcus Mergenthaler:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of abbreviations

DLB	Demand-led breeding
PEEP	Participatory Ex-antE Framework for Plant Breeding
FWER	family-wise error rate
p_{FR}	p-value Friedman-Test
p_W	p-value Wilcoxon signed-rank test
VCU	Value for Cultivation and Use
KPIs	key performance indicators

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2026.103142.

Appendix

A 1: Raw data table for descriptive and inferential statistical analysis of each closed question

Question	Wave	Median Likert Score	IQR	p Friedman	Chi^2	Df	Wave	p Wilcoxon
(B) Questions on the implementation of demand-led breeding (DLB) in Europe								
I am familiar with the concept or approach of demand-led breeding	1	4	1	0,0149956	8,4000	2	w1 vs w2	0,024752
	2	5	1	0,0149956	8,4000	2	w2 vs w3	0,989359
	3	5	1	0,0149956	8,4000	2	w1 vs w3	0,036663
Breeding priorities on legumes should be adapted depending on their end-use (e.g. food vs. feed vs. technical use)	1	4	1	0,0007603	14,3636	2	w1 vs w2	0,023411
	2	5	1	0,0007603	14,3636	2	w2 vs w3	0,148915
	3	5	0	0,0007603	14,3636	2	w1 vs w3	0,001904
It makes perfect sense to follow the demand-led breeding approach in European legume breeding	1	4	1,5	0,0969720	4,6667	2	w2 vs w3	0,275471
	2	4	1	0,0969720	4,6667	2	w1 vs w3	0,152093
	3	4	1	0,0969720	4,6667	2	w1 vs w3	0,051917
It is highly likely that in the medium term the demand-led breeding approach will become established in European legume breeding	1	3	1,5	0,0103158	9,1481	2	w1 vs w2	0,085874
	2	4	0,25	0,0103158	9,1481	2	w2 vs w3	0,358313
	3	4	0	0,0103158	9,1481	2	w1 vs w3	0,021248
I fully share the group opinion on the order in which the stakeholder groups should be considered	1 2 3	4	1					
(C) Which stakeholders along the value chain can provide the most useful information for shaping breeding priorities?								
Consumers with direct consumption (human nutrition)	1	4	1	0,3493349	2,1034	2	w1 vs w2	0,294160
	2	3	1,25	0,3493349	2,1034	2	w2 vs w3	0,850998

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Question	Wave	Median Likert Score	IQR	p Friedman	Chi^2	Df	Wave	p Wilcoxon
	3	4	1	0,3493349	2,1034	2	w1 vs w3	0,336281
Food processing ingredient producers	1	4	1	0,7007840	0,7111	2	w1 vs w2	0,477536
	2	4	1	0,7007840	0,7111	2	w2 vs w3	0,801614
	3	4	1	0,7007840	0,7111	2	w1 vs w3	0,211745
Food processing final product manufactures	1	4	1	0,5718815	1,1176	2	w1 vs w2	0,437406
	2	4	1	0,5718815	1,1176	2	w2 vs w3	0,824141
	3	4	1	0,5718815	1,1176	2	w1 vs w3	0,187462
Food analysis, food safety (private and public laboratories)	1	4	1	0,0383623	4,4000	2	w1 vs w2	0,040459
	2	3	2	0,0383623	4,4000	2	w2 vs w3	0,402348
	3	3	1	0,0383623	4,4000	2	w1 vs w3	0,137715
Feed processing companies	1	5	1	0,1737739	3,5000	2	w1 vs w2	0,119952
	2	5	0,25	0,1737739	3,5000	2	w2 vs w3	0,776814
	3	5	1	0,1737739	3,5000	2	w1 vs w3	0,119814
Animal nutrition (research and application)	1	4	1	0,0456683	5,1628	2	w1 vs w2	0,350648
	2	4,5	1	0,0456683	5,1628	2	w2 vs w3	0,279016
	3	5	1	0,0456683	5,1628	2	w1 vs w3	0,049816
Livestock farmers as users	1	4	1	0,8464817	0,3333	2	w1 vs w2	0,869143
	2	4	1	0,8464817	0,3333	2	w2 vs w3	1,000000
	3	4	0	0,8464817	0,3333	2	w1 vs w3	0,824407
Farmers as producers	1	4	1,5	0,5712091	1,1200	2	w1 vs w2	1,000000
	2	4	1	0,5712091	1,1200	2	w2 vs w3	0,304642
	3	4	1	0,5712091	1,1200	2	w1 vs w3	0,301412
Retailers and cooperatives	1	4	2	0,6838614	0,7600	2	w1 vs w2	0,617800
	2	4	1	0,6838614	0,7600	2	w2 vs w3	0,625928
	3	4	1	0,6838614	0,7600	2	w1 vs w3	0,745401
Advisory Services	1						w2 vs w3	0,440220
	2	3,5	1					
	3	3	1					
Cosmetology	1						w2 vs w3	0,607811
	2	2	1,25					
	3	2	1					
Medicinal Experts	1						w2 vs w3	0,675616
	2	3	1,25					
	3	3	1					
Seed producers	1						w2 vs w3	0,978594
	2	4	2					
	3	4	0					
Lobbying Institutions	1						w2 vs w3	0,435866
	2	2	1					
	3	2	1					
Chefs	1						w2 vs w3	0,081056
	2	3	2					
	3	3	1					

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Question	Wave	Median Likert Score	IQR	p Friedman	Chi^2	Df	Wave	p Wilcoxon
I fully share the group opinion on the order of which information could be helpful for creating targeted product or trait profiles of new varieties	1							
	2							
	3	4	1					
(D) Which information could be helpful for creating targeted product or trait profiles of new varieties?								
Related to agronomic performance (e.g. yield, yield stability, drought resistance, lodging resistance)	1	5	1	0,0288555	7,0909	2	w1 vs w2	0,119952
	2	5	0	0,0288555	7,0909	2	w2 vs w3	0,345779
	3	5	0	0,0288555	7,0909	2	w1 vs w3	0,024752
Related to specific crop characteristics (e.g. suitability for intercropping or harvesting purposes)	1	4	1	0,0483573	4,6383	2	w1 vs w2	0,617747
	2	4	2	0,0483573	4,6383	2	w2 vs w3	0,051747
	3	4	1	0,0483573	4,6383	2	w1 vs w3	0,036671
Regarding the visual or physical appearance of legume grains (e.g. colour, surface, size)	1	4	2	0,7746692	0,5106	2	w1 vs w2	0,791153
	2	4	0	0,7746692	0,5106	2	w2 vs w3	0,529651
	3	4	0	0,7746692	0,5106	2	w1 vs w3	0,488335
Regarding the visual or physical appearance of legume pods (e.g. wall thickness, bursting strength, size)	1	4	1	0,6065307	1,0000	2	w1 vs w2	0,768083
	2	4	1	0,6065307	1,0000	2	w2 vs w3	0,523035
	3	4	1	0,6065307	1,0000	2	w1 vs w3	0,644258
Regarding the visual or physical appearance of legume plants (e.g. length, leaf shape, growth and ripening behaviour, soil cover)	1	4	1	0,2318793	2,9231	2	w1 vs w2	0,121748
	2	3,5	1,25	0,2318793	2,9231	2	w2 vs w3	0,354474
	3	4	1	0,2318793	2,9231	2	w1 vs w3	0,654186
Regarding primary ingredients or nutritional content (e.g. protein content, fibre, starch, micronutrients)	1	5	1	0,4594258	1,5556	2	w1 vs w2	1,000000
	2	5	0,25	0,4594258	1,5556	2	w2 vs w3	0,371093
	3	5	0	0,4594258	1,5556	2	w1 vs w3	0,298618
Regarding secondary plant components (e.g. anti-nutritional factors, bitter substances, allergenic potential)	1	4	1	0,0408584	3,9200	2	w1 vs w2	0,374063
	2	5	1	0,0408584	3,9200	2	w2 vs w3	0,374063
	3	5	1	0,0408584	3,9200	2	w1 vs w3	0,047715
Regarding technological processing properties (e.g. dehulling efficiency, milling properties, cooking time)	1	4	1	0,6428393	0,8837	2	w1 vs w2	0,496514
	2	4	2	0,6428393	0,8837	2	w2 vs w3	0,392949
	3	4	0	0,6428393	0,8837	2	w1 vs w3	1,000000
Regarding labelling and transparency (e.g. “non-GMO”, “regionally adapted”, “low-input”)	1	4	2	0,0963276	4,6800	2	w1 vs w2	0,322385
	2	3	2	0,0963276	4,6800	2	w2 vs w3	0,374063
	3	3	1	0,0963276	4,6800	2	w1 vs w3	0,588081
Related to opinions on the speed of innovation in legume breeding	1	3	2	0,9478382	0,1071	2	w1 vs w2	0,922462
	2	3	2	0,9478382	0,1071	2	w2 vs w3	0,464435
	3	3	1	0,9478382	0,1071	2	w1 vs w3	0,631806
Regarding the price level of products based on legumes	1	4	2	0,0497871	6,0000	2	w1 vs w2	0,066362
	2	3	1	0,0497871	6,0000	2	w2 vs w3	0,402348
	3	3	1	0,0497871	6,0000	2	w1 vs w3	0,012738
Related to Economic KPIs	1						w2 vs w3	0,824407
	2	3	1,25					
	3	3	1					

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Question	Wave	Median Likert Score	IQR	p Friedman	Chi^2	Df	Wave	p Wilcoxon
Related to Crop rotation and precrop value	1						w2 vs w3	0,336281
	2	3,5	1					
	3	4	0					

Data availability

The data that has been used is confidential.

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