CANADIAN PLANT BREEDERS AND BIOINFORMATICIANS: FACTORS INFLUENCING DECISION MAKING AND KNOWLEDGE TRANSFER

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Introduction

This research was designed to better understand the uniquely, complex plant breeding work-flow, as well as plant breeders' decision-making processes in the context of new technology uptake.

Innovation implementation in plant breeding depends on the collaboration and cooperation work of plant breeders and bioinformaticians and/or IT developers. An increasing number of bioinformaticians and IT developers has been involved in the plant breeding process to assist breeders to manage the increasing number of databases that contain genomic information, as well as to help develop digital devices that breeders have started employing during the plant breeding process, such as drones, automated sensors, infrared cameras or various imaging tools. This process requires steady communication between bioinformaticians and breeders, as well as bioinformaticians' understanding of breeders' work-related needs and applications.

Objectives

Our research was developed with the aim of discovering and understanding the differences and similarities in opinions between Canadian public plant breeders and bioinformaticians/IT developers with regards to the plant breeding process flow and new technology adoption.

Therefore, we designed two questionnaires. One was directed to the plant breeding community and investigated how breeders perform their work and how they derive information from data under the following four aspects: knowledge, process, people and technology. The other questionnaire, containing in-mirror questions, was directed to the bioinformatics community (including IT developers) to investigate how well they know plant breeders' work-flow and work-related issues and decisions on the same four aspects.

The overall objective was to line up the answers between these two questionnaires to find out whether there is a convergence or a disconnect of knowledge and opinions, and eventually inform both parties involved about topics that need clarification and increased communication.

Methodology

The research has been carried out by using a survey focused on Canadian plant breeders, plant breeders' assistants, bioinformaticians and IT developers who are employed in public institutions (academia and government), and who work together to develop and anticipate impacts of scientific advances in genomics.

The survey was open between March 2021 and 2022. The survey was filled out by 26 breeders and 25 bioinformaticians. The survey designed for breeders contained 45 questions ranging from open-ended, yes/no, Likert scale or ranking type of questions. The survey designed for bioinformaticians contained 26 questions. As respondents did not answer various questions throughout the survey, the number of respondents (*n*) reported for each question varies.

Major findings of the survey:

- Breeders and bioinformaticians' opinions converged when ranking plant breeders' essential skills and competencies. Both categories ranked education first, followed by hands-on experience with the plant, while statistical and data analysis ranked third.
- A third of the bioinformaticians and IT developers reported not knowing how breeding priorities are determined for plant breeders nor who makes critical selection decisions during the breeding process. Although prompted with the option 'team effort', the remaining of the bioinformaticians identified breeders as the sole decision makers.
- The opinions of the two categories of respondents were similar when asked what type of information breeders regularly look up when they make selection decisions during the plant breeding process. Both groups mentioned 'field notes', 'multi-year analyzed data', as well as 'field data collected by technicians and field crew'.
- Most breeders are quite aware that 'knowledge of latest technological development' is an essential skill for them, and in a couple of instances they expressed interest in learning more about bioinformatics and artificial intelligence.
- When asked what digital devices breeders use in their breeding program, the main difference between the two groups of responses is that bioinformaticians and IT developers believe that breeders and plant breeders' assistants employ certain digital devices to a higher degree than breeders indicate their use. A few examples are imaging tools (76% of bioinformaticians versus 46% of breeders), automated sensors (64% versus 33%) and RGB or infrared cameras (68% versus 38%).
- In their breeding programs, both indoor and in the field, a majority of breeders access both internal and external databases (54%). However, more than a third of the bioinformaticians and IT developers acknowledged that they are not sure what type of databases breeders' access in their breeding work or how often they access them.
- When breeders were asked to share with us three databases that come to their mind, besides the expected wide range of database names, their responses revealed that breeders' own internal databases are essential for them. In contrast, bioinformaticians did not identify the importance of 'internal or own databases'. The database that bioinformaticians mentioned the most is the KnowPulse database, which indicates their awareness about it.
- Breeders were asked a set of questions designed to indicate their intention to use 'omics in their future work as well as their current usage and knowledge of the topic. Around 70% of breeders believe that 'omics usage increases their productivity and enables faster accomplishment of tasks. However, even though using 'omics does not take too much time from the breeders' normal duties, it seems that finding the desired 'omics and extracting the information from the 'omics data are not seen as easy tasks. Briefly, a majority of breeders have the behavioral intention of using 'omics in their work.

Conclusions

The results of the survey of breeders and bioinformaticians illustrate the topics where the two groups' opinions and perspectives converge or differ. It was expected and reasonable that bioinformaticians would not have the same information and opinions as breeders with respect to all the various subjects that are particularly related to breeders' work and their accumulated knowledge and experience. The goal of this survey was to identify if and where the information gaps exist, and to improve the communication channels between the two categories of respondents with the aim of achieving better technology development and implementation in the plant breeding work.

Considering the two groups targeted in our research, Canadian plant breeders and bioinformaticians who work with plant breeders in an academic or government facility, as well as the small number of complete surveys, these results should be interpreted accordingly, without expanding or generalizing the findings. In other words, the qualitative information (e.g. respondent's answers to open-ended questions) should be reflected upon while considering the quantitative information obtained from a distinct group of experts.

Answers converged in many instances and various topics, such as when ranking plant breeders' essential skills and competencies or when learning what type of information breeders regularly look up when they make selection decisions during the plant breeding process.

One notable gap is that bioinformaticians are not that aware of the importance that breeders' team plays for a plant breeder. Breeders not only get information and details when needed during the breeding process, but they also involve their teams when making critical selection decisions. This information should perhaps be considered during the consultation sessions between breeders and bioinformaticians, as team members could be included and contribute to discussions about technology development and improvement.

Another discrepancy in responses was related to the digital devices that breeders currently use in their breeding program. Bioinformaticians and IT developers had the impression that breeders and plant breeders' assistants employ digital devices such as automated sensors or imaging tools to a higher degree than breeders indicate that they actually use. Thus, a conversation between breeders and bioinformaticians would help breeders to increase the usage or explain what discourages them from employing more such devices.

Many bioinformaticians contribute to the development and organization of breeders' various databases. However, many of them do not know what type of databases (internal or external) breeders' access in their breeding program, both indoors and in the field. Further, many of them do not know how often breeders access their databases, and those who know assumed breeders access the databases way less often than breeders indicated they do. Breeders clearly indicated the frequent use of their own internal databases. This is important to be known and discussed by both groups of respondents, as breeders who access their internal databases quite often may benefit from bioinformaticians' assistance in terms of organization, formulating queries, or obtaining the result of interest only, and not a variety of unnecessary data. This would save breeders valuable time and increase their work efficiency.

Last, but not the least, although the qualitative research methodology does not allow interpreting the answers of the open-ended questions, breeders and bioinformaticians responses with regards to what would improve the plant breeding work reinforce how crucial is the need of communication improvement between the two categories of respondents.

2. Introduction

The Food and Agriculture Organization (FAO, 2017) estimated that food production must increase by 60% to satisfy the growing food demand in the next decades, and therefore, urgent action must be taken to develop and commercialize innovative technologies that ensure sustainable agriculture. With deeper knowledge of genomics, plant breeding can play a critical role in the agricultural ecosystem by delivering superior varieties that will meet the future demands for global food and nutritional security as well as environmental sustainability, all the while maintaining profitability for farmers.

Plant breeding has experienced tremendous technical progress over the past few years. In theory, breeding programs set up priority breeding targets in consultation with the end-users, who readily adopt and implement new technologies to improve their performance. The reality often is, however, not this straightforward. Most breeding programs have been continuously confronted with a huge amount of data, even prior to the explosion of digital data generated by genome sequencing and novel phenotyping techniques. The breeder is constantly required to make timely decisions, both for short-term uses (e.g. selecting plants to move to the next generation) and long term investments (e.g. adopting new tools to improve their practice).

Recent advances in ‘omics research have led to a dramatic growth in digital data and novel techniques available to the breeders. The availability of this kind of data should, theoretically, provide scientists and plant breeders more comprehensive information to address both basic and applied research questions. However, big data brings the challenge of actually using and transforming it into decision-relevant knowledge. Too much uncoordinated information could easily lead to “data paralysis” and decrease the actual technology uptake for typical breeding practices. How breeding programs evaluate and decide to make use of new data and technologies that are developed by external R&D partners is not well understood.

Designed for observing plant breeders’ work-flow and understanding their needs related to new technology uptake, our research was developed with the aim of discovering and understanding the differences and similarities in opinions between Canadian public plant breeders and bioinformaticians/IT developers with regards to the plant breeding process flow and new technology adoption.

An increasing number of bioinformaticians and IT developers has been involved in the plant breeding process to assist them in managing the increasing number of databases that contain genomic information, as well as to help develop digital devices that breeders have started employing during the plant breeding process, such as drones, automated sensors, infrared cameras or various imaging tools. This requires steady communication between breeders and bioinformaticians, and a good understanding of breeders’ work-related needs and applications. Therefore, we designed two questionnaires.

3. Objectives

One questionnaire was directed to the plant breeding community to investigate how they perform their work and how they derive information from data under the following four aspects: knowledge, process, people and technology. The other questionnaire, containing in-mirror questions was directed to the bioinformatics community (including IT developers and specialists) to investigate how well they know plant breeders' work-flow and work-related issues and decisions on the same aspects (knowledge, process, people and technology). The overall objective was to line up the answers between these two questionnaires to find out if there is a convergence or a disconnect of knowledge and opinions, in order to inform both parties involved about the opportunities for better communication.

The survey questions included: Which databases are breeders using in their breeding programs? What would make them use, or increase the use of databases? How does data availability affect decision-making during the plant breeding process? The introduction of visualization tools complicates this process. People process personal observations, databases (e.g. of genome sequences), statistics (from experiments) and images (e.g. images from cameras) differently. Each is proffered to bring real value to breeders, but we do not know how breeders would prefer to have such complex and varied information organized. What would be an ideal structure of datasets for use in their selection process? Given the complex and subtle combination of art and science needed in phenotyping, breeders can provide background into what is needed to complement their knowledge, experience, intuition, and/or judgment in the decision-making process during the selection process.

4. Methodology

The present survey was approved by the U of S Behavioural Ethics Board (Beh. ID #2472) in March 2021 to be carried out as an online survey. Emails sent to potential respondents contained a brief explanation of our research questions, the survey link, and a consent form that informed respondents that participation in the survey is voluntary, and that they can choose to not answer questions with which they feel uncomfortable. Also, confidentiality terms and data storage and safety were explained.

As our goal was to learn more about plant breeders and bioinformaticians engaged in public Canadian institutions, we were aware that this would restrict the number of potential respondents. This meant that our analysis is largely qualitative, as the low number of responses does not allow for statistical significance. To increase participation, we decided to include plant breeders' assistants as well in our breeders' database. Therefore, we had two databases of potential participants: one containing email addresses of plant breeders and their assistants and one containing email addresses for bioinformaticians and IT developers working closely with breeders.

Using the SurveyMonkey survey platform, the survey was emailed to 50 public breeders and breeders' assistants, out of which 38 people decided to fill it out. Breeders were presented with 45 questions. However, as respondents were told that they can answer only the questions they want to, the final number of complete surveys was 26. The term "complete surveys" does not mean that all questions had a response. There is a certain algorithm employed by SurveyMonkey, which calculates whether a survey is ‘complete’ or not, depending on the number of total questions of survey and the number of answered questions.

As a result, the number of respondents (*n*) for each question varies and is reported for each question throughout this report in the associated text, table or figure. The survey directed to breeders contained a total of 45 questions, ranging from open-ended type to Likert scale or ranking type of questions.

Similarly, using the same survey platform, we had emailed the survey to 60 bioinformaticians and IT developers who were working and interacting with breeders to create ‘-omics’ databases (genomics, phenomics, metabolomics, etc.) as well as visual analytics tools for improved plant breeding, including drones, automated sensors, infrared cameras, and other various imaging tools. The number of complete responses was 25. Bioinformaticians and IT developers had to answer 26 survey questions. The difference in the number of questions for the two categories of respondents was because breeders were asked additional questions related to their professional expertise.

Both surveys were open between March 2021 and March 2022. Response rates were particularly low in the midst of the ongoing pandemic. We realized that this situation was not unique to our research, and that globally, people were more reluctant to use their work or spare time completing a survey. The challenges of survey research were acknowledged by social science researchers all over the world (Grandstaff and Webber, 2021; U.S. Dept of Labour, 2022). Various reasons played a role into this situation: social distancing, working from home and other restrictions led to an increased number of online surveys; also, people were spending enough time in front of a computer for work and prioritized their spare time, etc. To address the initial low response rate and incomplete responses, we kept searching for potential respondents, we emailed personalized messages containing the survey link, we revised and shortened the invitation memo and the cover letter. Further, we constantly updated our email databases trying to include as many potential respondents as possible.

5. Respondents’ overview

The first question asked respondents what their current work position is. For breeders, the answer options presented included breeders, plant breeders’ assistants, and trait developers. For all questions, and for both surveys, respondents had the opportunity to add any comments or responses besides the options provided. As shown on Figure 1, most of the respondents were plant breeders (68%). Retired plant breeders, plant breeders’ assistants and trait developers counted for 8% each. One respondent wanted to clarify that their current position is *technologist* and another one that their job is related to *germplasm development and characterization*.

With regards to bioinformaticians’ survey, responses indicate that out of 25 respondents for each category, 64% were bioinformaticians and 16% IT developers. Five respondents stated that their current job is *professor* (8%), *researcher* (8%) and *data curator* (4%).

Figure 1. Respondents' current work position

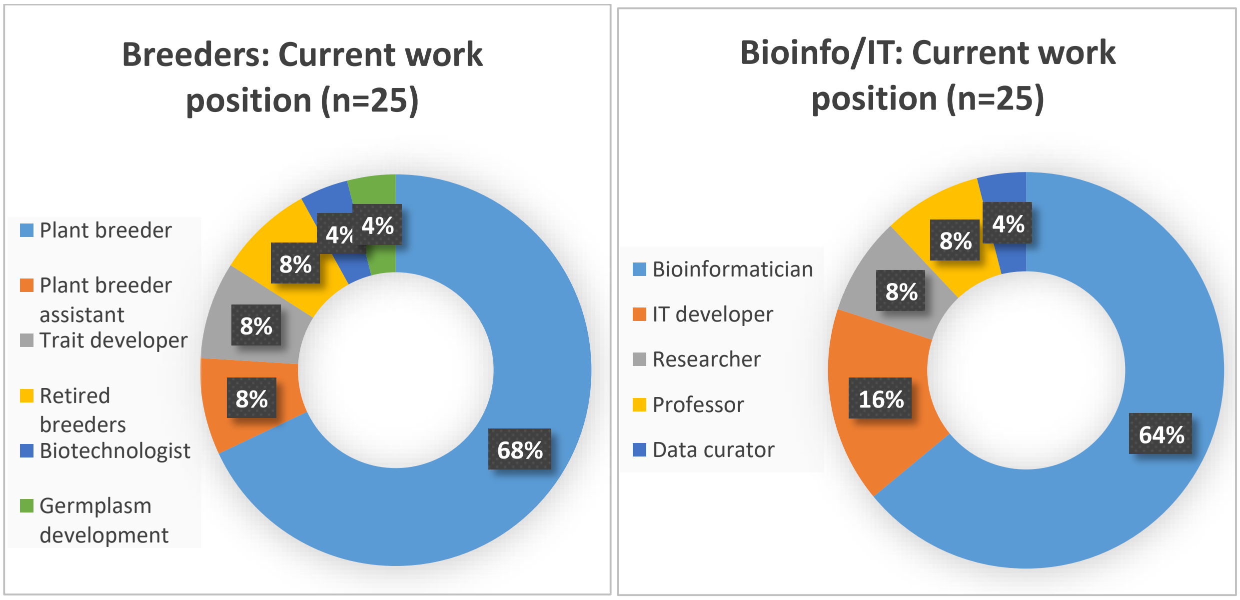
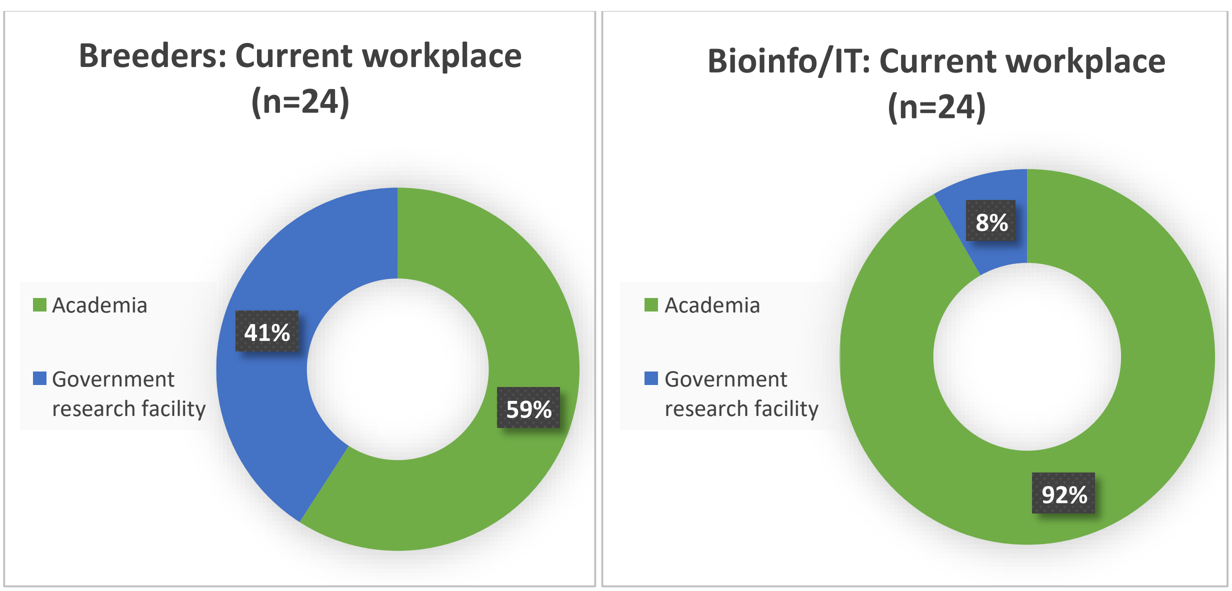


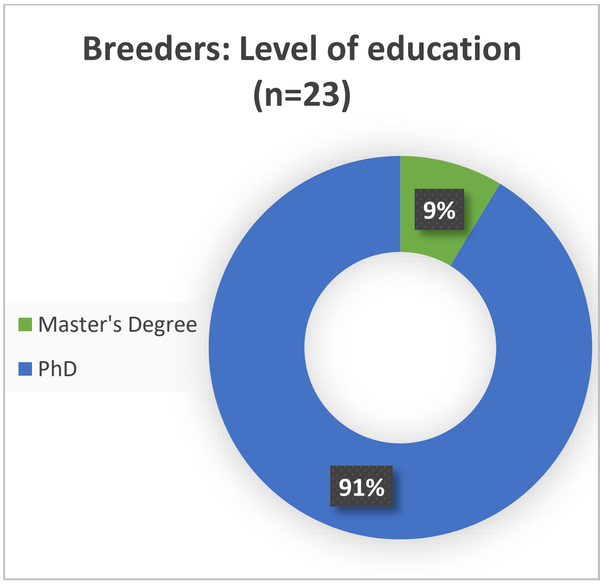
Figure 2 illustrates that more than half of the breeders who filled out the survey currently work in academia (59%), while the rest work in a government research facility (41%). With regards to the bioinformaticians, most cited their current workplace as academia (91%); only 8% reported being employed in a government research facility.

Figure 2. Respondents' current workplace



Regarding the education level, Figure 3 shows that out of 23 respondents, most breeders (91%) have a PhD, and the rest (9%) a Masters' degree. Almost half of the bioinformaticians and IT developers have a PhD (46%), one third (33%) have some undergrad degree while the remaining of the respondents (21%) have a Masters' degree.

Figure 3. Respondents' level of education



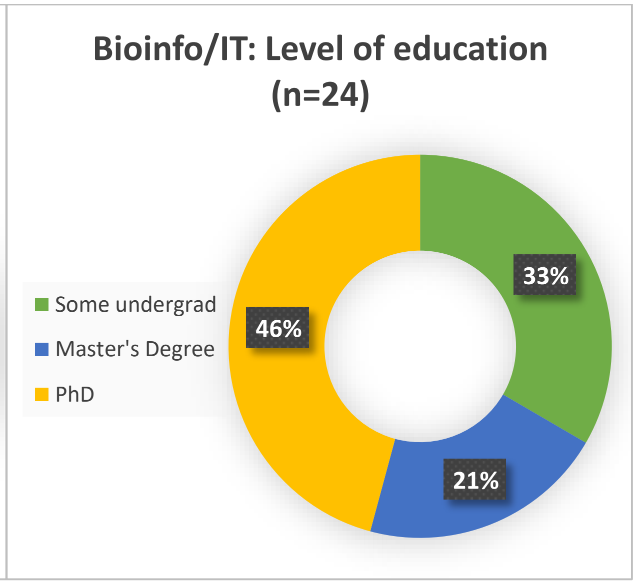
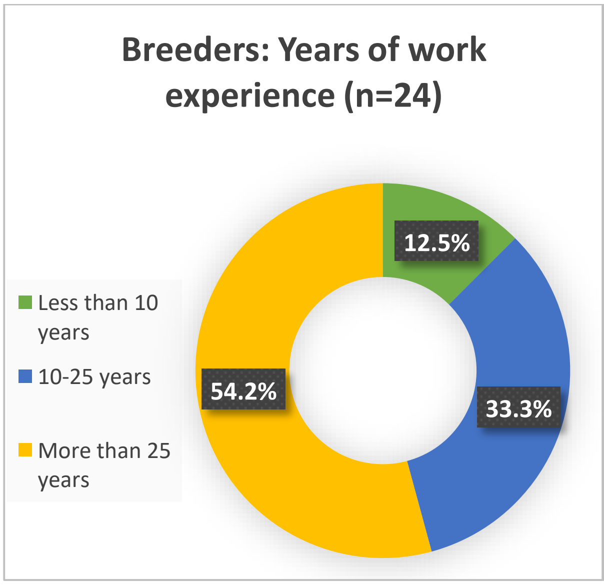
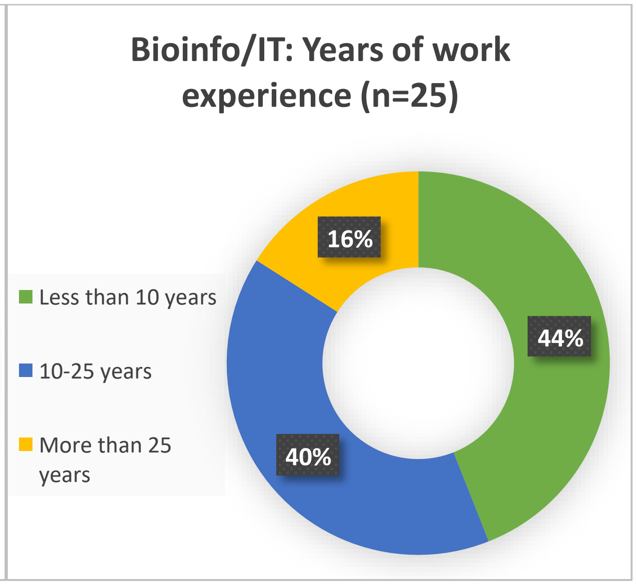


Figure 4 presents breeders and bioinformaticians' years of work experience. More than half of the breeders (54.2%) have over 25 years of experience, 33.3% between 10 to 25 years and 12.5% less than 10 years. Of the 25 bioinformaticians and IT developers who answered this question, only 16% have more than 25 years of experience, 40% have between 10 to 25 years and 44% have less than 10 years. Comparing the two groups, it can be observed that breeders have significantly more work experience than bioinformaticians and IT developers, for the 'more than 25 years' category, while the latter group has a bit more experience in the '10-25 years' category.

Figure 4. Respondents' work experience

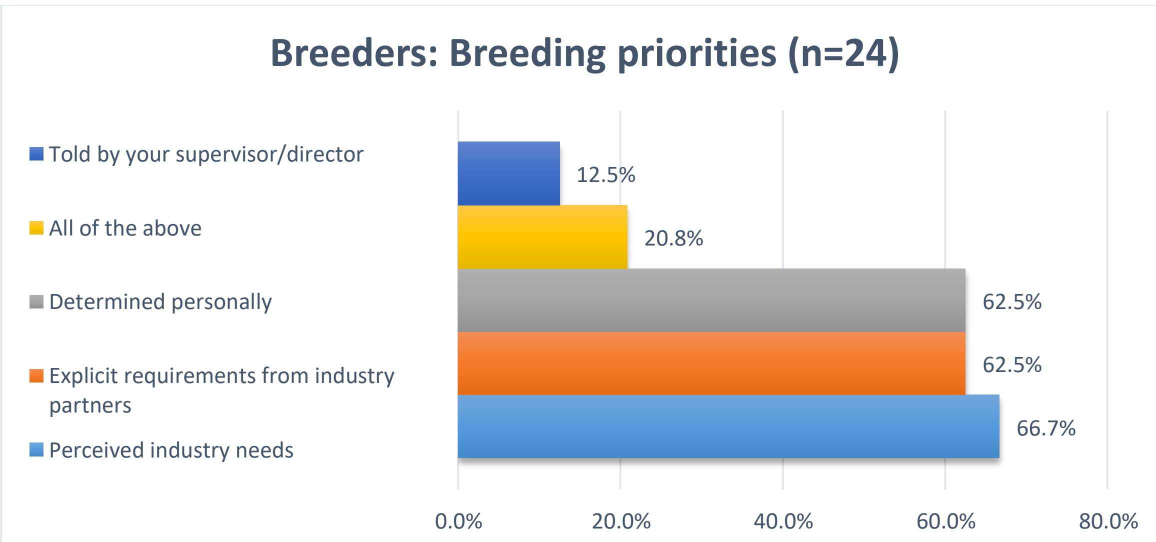




6. Breeding priorities and decisions

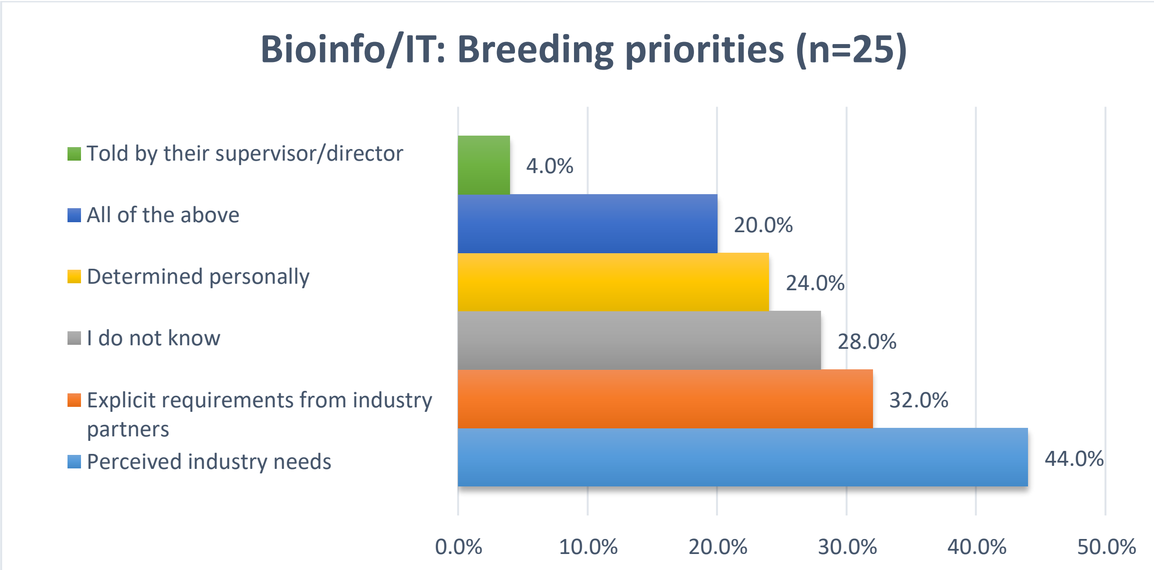
The next question explored how breeding priorities are determined; respondents were asked to choose all the applicable options. The percentages shown in Figure 5 indicate that, for breeders, 'perceived industry needs' was the most common response with 66.7%, followed swiftly by 'determined personally' and 'explicit requirements from industry partners', both with 62.5% of the total options. The 'all of the above' (20.8%) option endorses the validity of the first three choices. In the Comments section, breeders clarified that breeding priorities are variously set by '*government goals*', '*interactions with other scientists, particularly breeders*', and '*product profiles developed collaboratively*'.

Figure 5. Breeding priorities - breeders



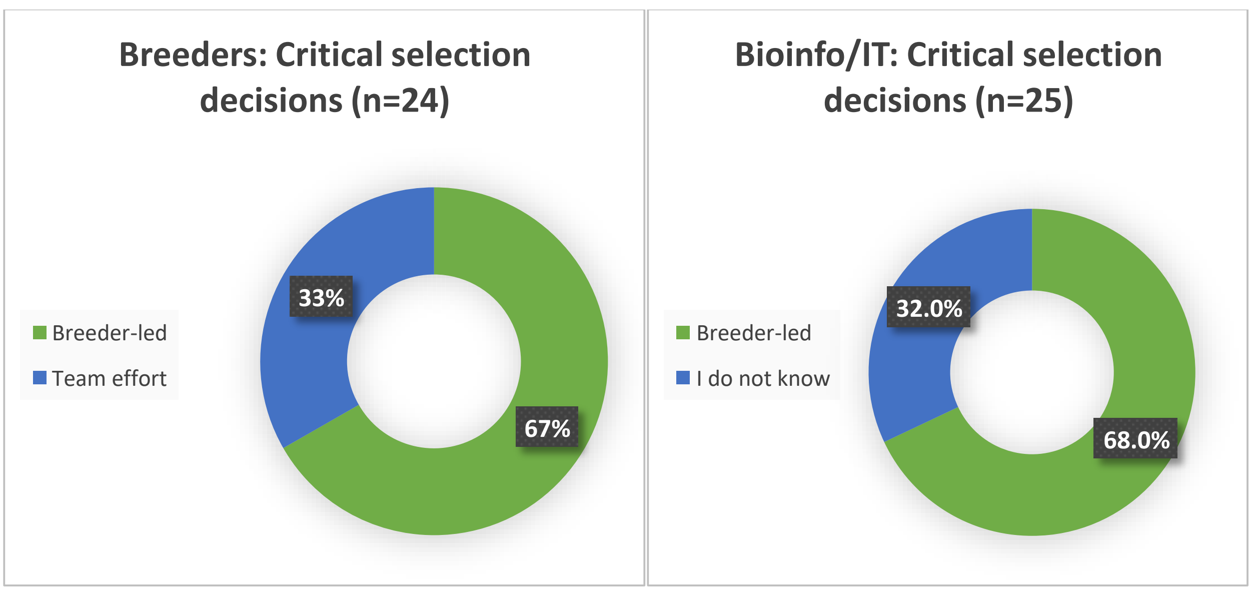
The other group of respondents, the bioinformaticians and IT developers, was asked how they think breeding priorities are being determined for plant breeders. As shown in Figure 6, respondents believe that 'perceived industry needs' is the lead reason but only at 44%), followed by 'explicit requirements from industry partners'. However, an important percentage of bioinformaticians (28%) acknowledge that they do not know how breeding priorities are determined. Further, 24% think that priorities are determined personally by breeders and 20% chose the 'all of the above' option and only 4% think they are 'told by their supervisor/director' (Figure 6). One bioinformatician also commented that breeding priorities are being set by '*funding agencies*'.

Figure 6. Breeding priorities – bioinfo/IT



Further, respondents were asked how critical decisions are made during the selection process. The difference of opinions between the two groups of respondents is shown on Figure 7. While breeders acknowledge the team efforts in the decision-making process (33%), bioinformaticians seem not to be aware of the key role played by all the members of the breeding team. Even though they were also prompted with the 'team effort' answer option, 32% of bioinformaticians and IT developers answered that they do not know who else is taking critical selection decisions.

Figure 7. Critical selection decisions



7. Essential skills and competencies

The next question inquired about the essential skills and competencies of a plant breeder (Figure 8). All breeders answered this question and chose 'education' as the main competence (95.7%), closely followed by 'hands-on experience with the plant' (91.3%), 'statistical and data analysis' (91.3%), 'experience with the industry sector' (87%), and 'knowledge of the latest technological development' (78.3%). 'Physical abilities' and 'experience with farm machinery operations' were less popular choices for breeders, summing up to 34.8% and 26.1% of all responses, respectively.

Besides the answer choices presented to them, a few breeders decided to clarify their opinions by adding comments in the 'Other' field. Thus, one person indicated that all the options presented are important, as well as *'common sense and decision-making abilities'*. Another respondent added that '*social skills are needed too, as the breeder has to be part salesperson'*. Another breeder listed as essential skills and competencies *'management and business skills'* and '*understanding your crop as both a species and a commodity'*. One respondent considers that '*a PhD is not necessary, but some education is*', while another respondent highlighted the need to have '*knowledge of current agronomy and production methods of the crop being bred'*.

Figure 8. Essential skills and competencies - breeders

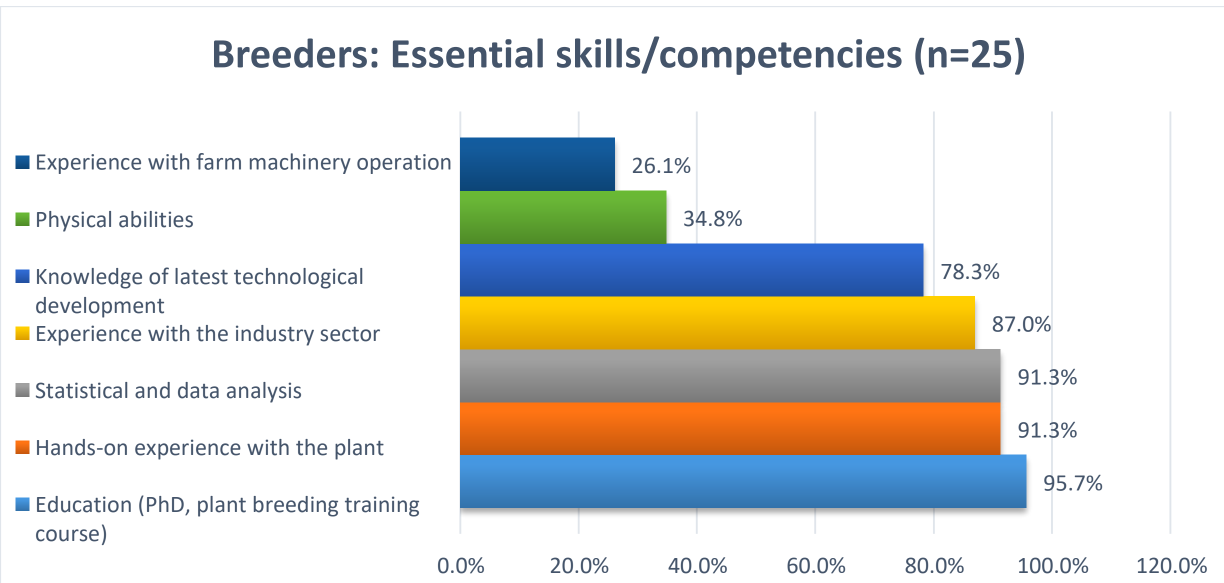
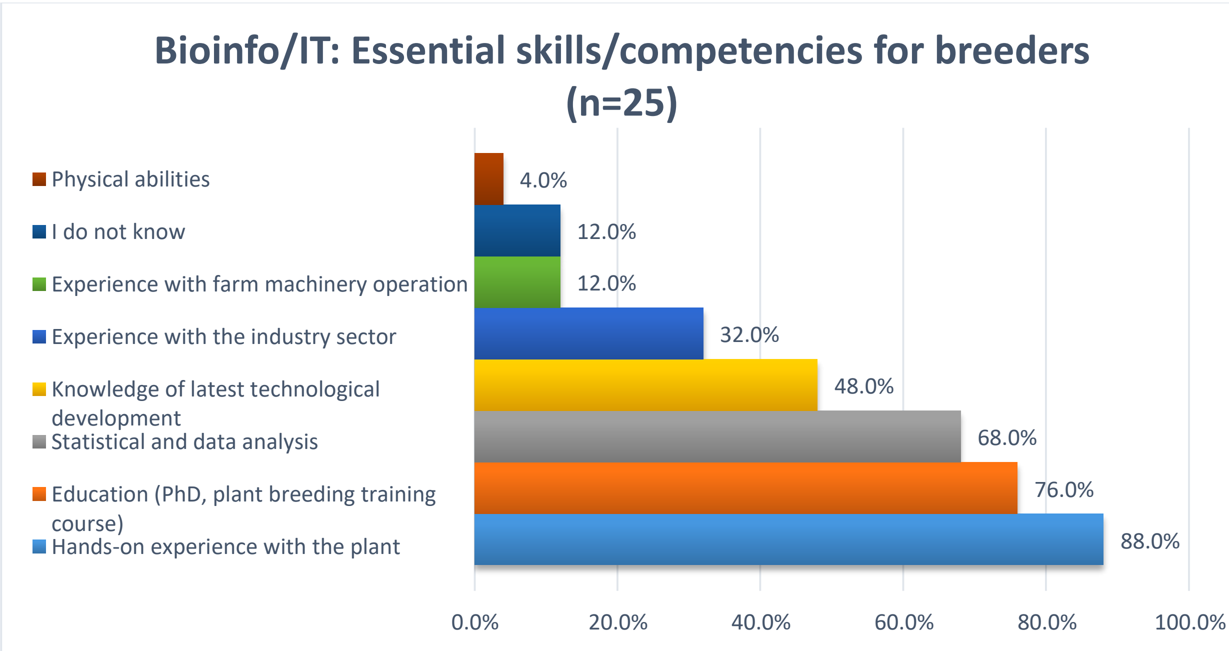


Figure 9 shows that most of IT developers consider that the 'hands-on experience with the plant' is the key competence for plant breeders (88%), followed by 'education' (76%), and 'statistical and data analysis' (68%). It is interesting to observe that less than half of the bioinformaticians (48%) consider that the 'knowledge of latest technological development' is an essential skill for breeders. This option was chosen by 78.8% of the breeders, which shows breeders' awareness of new technology knowledge in their profession. Further, only one third (32%) of the bioinformaticians consider that 'experience in the industry sector' would represent an essential competency for breeders, in contrast with breeders' choices that sum up to 87%. Only a few bioinformaticians and IT developers (12%) stated that they do not know what essential skills and competencies breeders should have.

Two comments were added in the 'Other' field option. One respondent shared that it is the '*intuition. It seems to be a bit of an artform*'. Another IT developer added that '*it depends on the species. Species with elite genetics need advanced skills. Others can make due with simple selections*.'

Figure 9. Essential skills and competencies – bioinfo/IT



A subsequent question was intended to help clarify the answers presented in Figures 8 and 9. Respondents were required to rank their top three options from the previous question in the order of importance, where 1 is the most important. However, not all respondents answered this question, and some of them ranked only their first option, or only the first and second option. This is the reason why the number of respondents is mentioned for each category.

As Table 1 illustrates, out of the 22 breeders who ranked their own choices, 68.2% had ranked 'education' on the first place, while 31.8% had ranked it on the second place. Further, out of the twenty respondents who ranked the 'hands-on experience with the plant' option, 25% had it in first place, 65% in second place and 10% in third place. A total of 12 respondents ranked the 'statistical and data analysis': 14.3% in first place, 7.1% in second place and 64.3% in third place.

Table 1. Most important three skills/competencies - breeders

Breeders: Categories (total no. of respondents)	First	Second	Third
Education (n=22)	68.2% (15)	31.8% (7)	0
Hands-on experience with the plant (n=20)	25.0% (5)	65.0% (13)	10.0% (2)
Statistical and data analysis (n=12)	14.3% (2)	7.1% (1)	64.3% (9)

IT developers and bioinformaticians also chose the three categories: education, hands-on experience with the plant and statistical and data analysis; their percentages are only slightly different when compared to the breeders'. Thus, 15 respondents had ranked 'education' in first (60%) and second place (40%) (Table 2). Further, out of 20 respondents, 40% ranked 'hands-on experience first, and 30% ranked it second and third, respectively. Out of thirteen bioinformaticians, 23.1% had ranked 'statistical and data analysis' in first place and 38.4% in second and third place, respectively.

Table 2. Most important three skills/competencies - bioinfo/IT

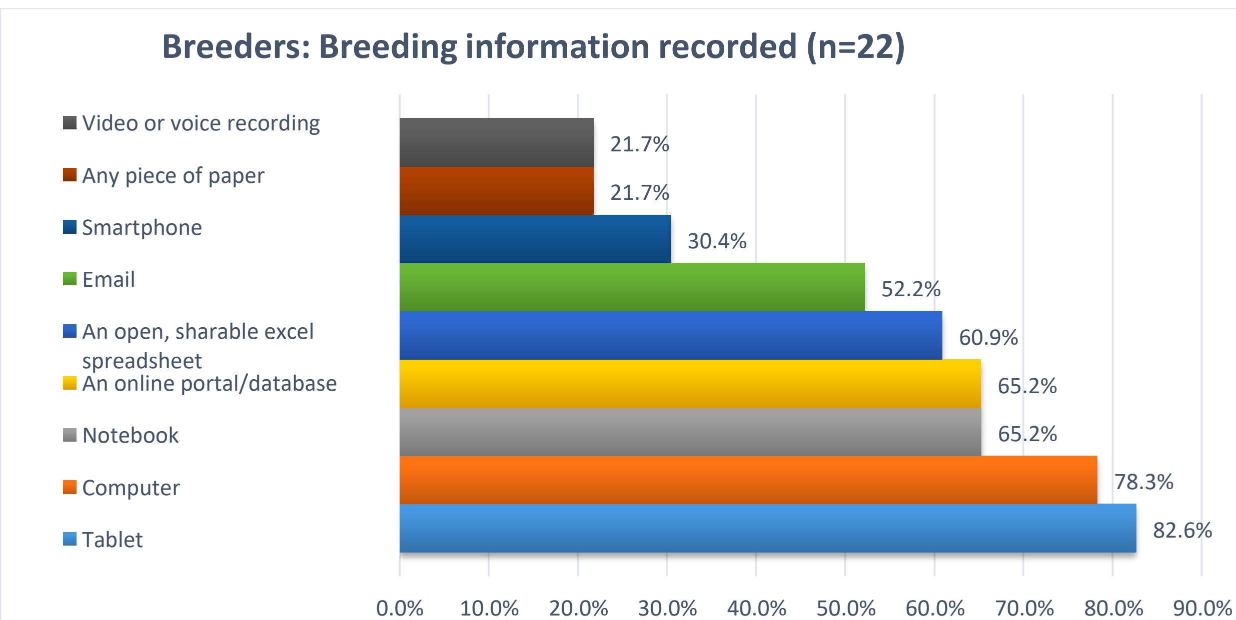
Bioinfo/IT: Categories (total no. of respondents)	First	Second	Third
Education (n=15)	60.0% (10)	40.0% (6)	0
Hands-on experience with the plant (n=20)	40.0% (8)	30.0% (6)	30.0% (6)
Statistical and data analysis (n=13)	23.1% (3)	38.4% (5)	38.4% (5)

8. Recording and seeking breeding information

Next, survey participants were asked how the breeding information is recorded and communicated during the plant breeding process. Again, they were asked to choose all options that apply in their case.

Figure 10 shows that most breeders indicated that they use mainly tablets (82.6%) and computers (78.3%) to record information. 'Notebooks' and 'online portals or databases' responses were equally selected by respondents (65.2%) closely followed by 'an open, sharable excel spreadsheet' (60.9%). More than half of the breeders (52.5%) use 'email' to record breeding information, while 30.4% of them use 'smartphones', and 21.7% use 'any piece of paper' as well as 'video or voice recording'.

Figure 10. Recording breeding information - breeders

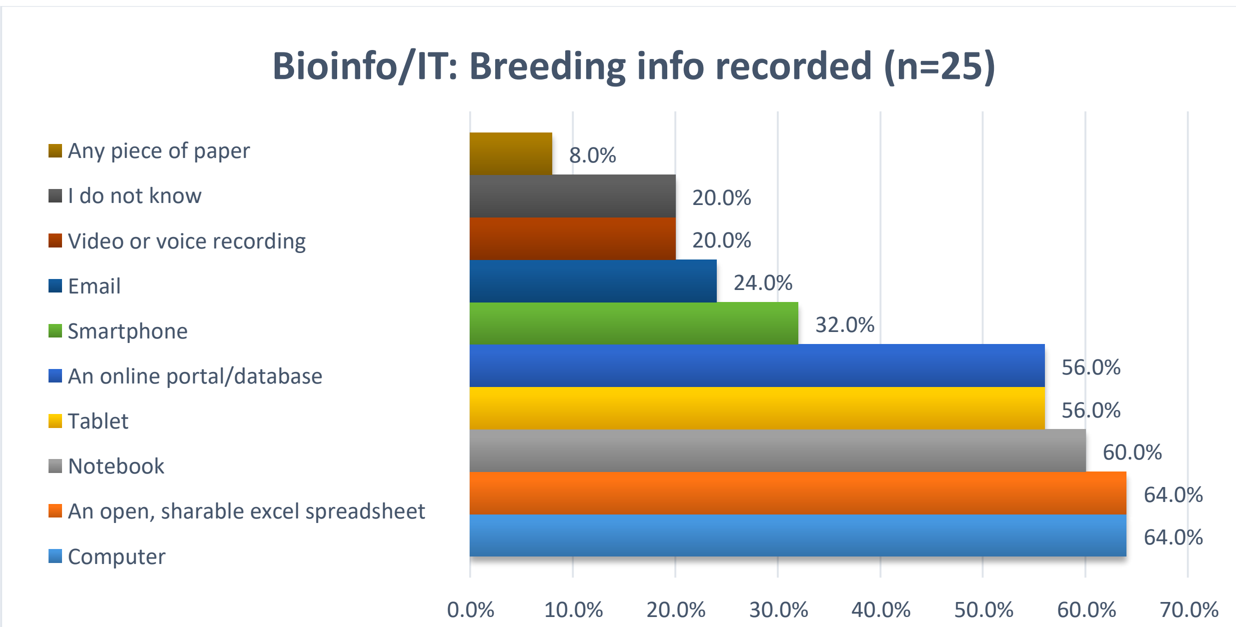


The majority of bioinformaticians and IT developers (Figure 11) considered that breeders prefer to record breeding information on ‘computer’ (64%), an ‘open sharable excel spreadsheet’ (64%), ‘notebook’ (60%), ‘tablet’ (56%) and an ‘online portal/database’ (56%). The use of ‘smartphone’ (32%) and ‘email’ (24%) had fewer choices from this category of respondents. Also, only 20% of the bioinformaticians and IT developers considered that breeders use ‘video or voice recording’ and only 8% of them opted for ‘any piece of paper’. Further, 20% of the respondents acknowledged that they do not know how the breeding information is recorded during the breeding process.

For this question, one of the main discrepancies between the two categories of respondents is the use of the tablet. While most breeders prefer to use the tablet (82.6%), only slightly more than half (56%) of bioinformaticians and IT developers had chosen this option.

Another notable difference is that breeders use their email (52.2%) to record breeding information way more than their counterparts recognize (24%). Other differences in responses refer to the use of the computer, 78.3% of breeders’ choices versus 64% of bioinformaticians’, and the use of pen and paper, where 21.7% of breeders use this method to record information, while only 8% of the bioinformaticians chose this option.

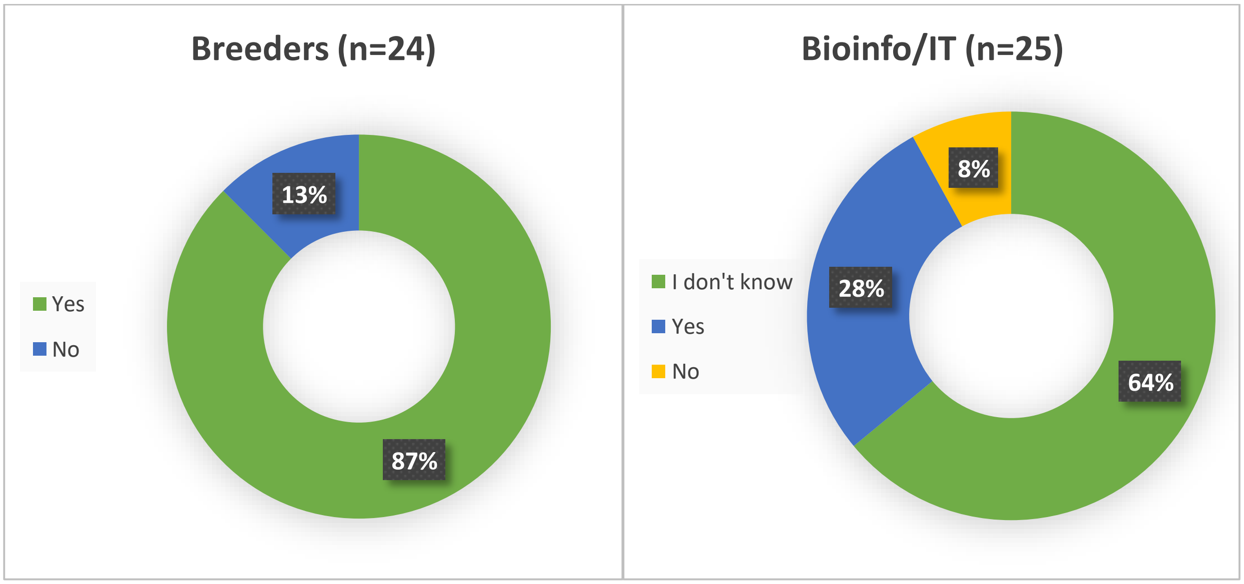
Figure 11. Recording breeding information – bioinfo/IT



We then asked breeders whether they are happy about how the information is captured and communicated to them during the plant breeding process (Table 12). Out of 24 respondents for this question, 87.5% indicated that they are happy, while 12.5% that they are not happy with how the information is captured and communicated to them.

IT developers and bioinformaticians were also asked whether they think breeders are happy about how the information is captured and communicated to them during the plant breeding process. Out of 25 respondents, 64% acknowledged that they do not know, 28% think breeders are happy, and 8% believe breeders are not happy with how the information is captured and communicated to them.

Figure 12. Whether plant breeders are happy with how the information is presented to them



For the next question, **only breeders** were asked whether they have a brief suggestion for improvement with regards to how they would prefer to have the information presented to them. Fourteen breeders and breeders' assistants shared their thoughts and suggestions. Table 3 illustrates the answers of the remaining eleven breeders and plant breeders' assistants.

Table 3. Suggestions for improvement when presenting breeding information

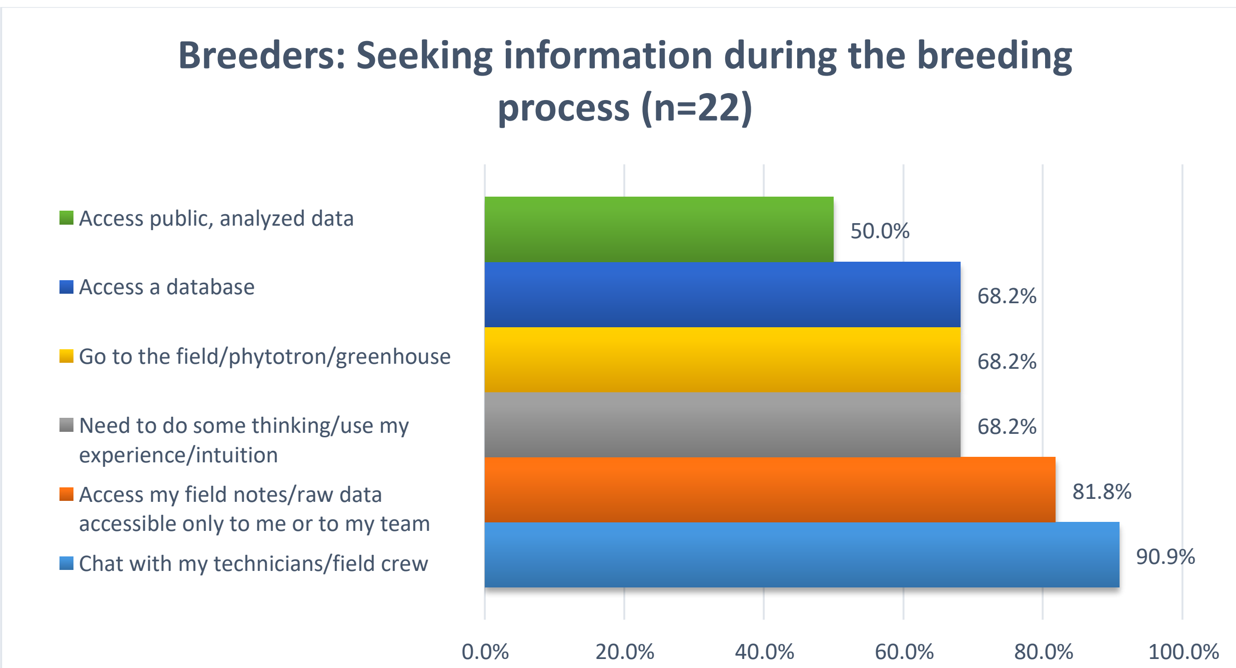
No.	Responses
1	*Lead plant breeder needs to be active in the field - plant breeding is still part art (experience) and familiarity with material in the field.*
2	*These are program dependent. Our system is constantly evolving to take into account new data types.*
3	*Arranged structured database in excel preferred.*
4	*Information needs to be accessible through relational database.*
5	*Photographs.*
6	*IoT, shared network drives, smartphone-based apps etc.*
7	*We could make more use of plant breeding software to centralize data.*
8	*It would be nice to have the resources to make decisions faster, particularly with genomic data.*
9	*Assembly and presentation of data for selecting parents for crossing needs improvement.*
10	*Flexibility to change over time - reports, data types, analyses.*
11	*Online portal allows for rapid and efficient transfer and use of all data.*

With regards to improvements in presenting breeding information, plant breeders' had a wide range of suggestions, including structured databases in an excel format, the need for relational databases, photographs, shared network drives, smartphone apps, software to centralize data, or online portals. Other thoughts that breeders shared in the survey either emphasized the need for resources to make faster decisions with genomic data or the need for improvement in the assembly and presentation of data for selecting parents for crossing.

In the following question, respondents were asked where they seek if they need more information during the breeding process. Figure 13 shows that almost all breeders (90.9%) indicated that they turn for information to their technicians or field crew. The next choice, also preferred by a significant number of breeders (81.8%) involves accessing the field notes and raw data available, but only among the team. Equally ranked (68.2%) were the 'need to do some thinking/use my experience/intuition', 'go to the field/phytotron/greenhouse', and 'access a database'. Half of the respondents indicated that they also access public, analyzed data, such as internal field data or data from the provincial seed guide.

In the comments field, breeders added that '*planning ahead*' is one of their strategies when they need more information during the breeding process, as well as '*accessing breeding literature*'. One respondent highlighted the importance of '*consulting with breeding colleagues and scientists doing research on the crop, searching the internet, and reviewing information on germplasm*'.

Figure 13. Seeking information during the breeding process - breeders

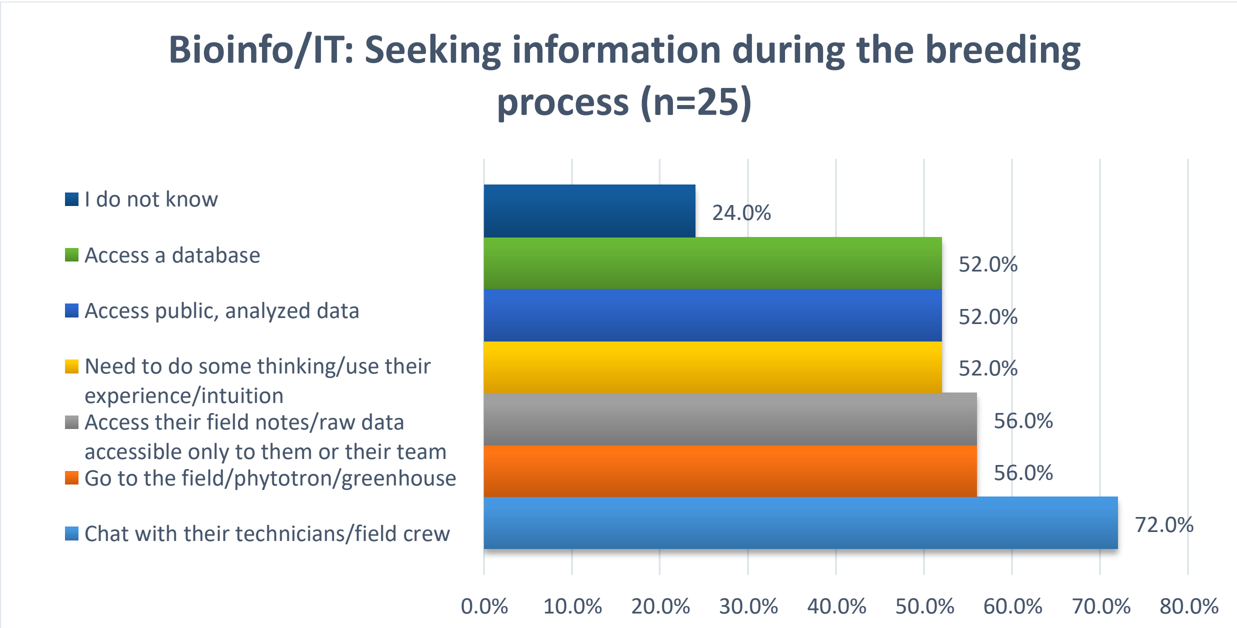


Similarly, bioinformaticians and IT developers were asked to share their opinion on how they think breeders seek information during the breeding process when they need additional information. Figure 14 illustrates that almost three-quarters of bioinformaticians (72%) are aware that breeders first chat with their 'technicians or field crew'. A bit more than half of the IT developers (56%) believe that breeders go to the 'field/phytotron/greenhouse' and access their 'field notes or raw data' available only to them. Further, half of the respondents (52%) see the following three options as equally important:

the 'need to do some thinking/use their experience/intuition', 'accessing public data', and 'accessing a database'. Almost a quarter stated that they do not know how breeders seek extra information.

Comparing the responses of the breeders and bioinformaticians, it can be noted that 24% of the bioinformaticians do not know how breeders get additional information when needed during the breeding process, and this impacts the remaining percentages' values. However, the first choice, of chatting with their team members, converged toward the first place for both categories analyzed.

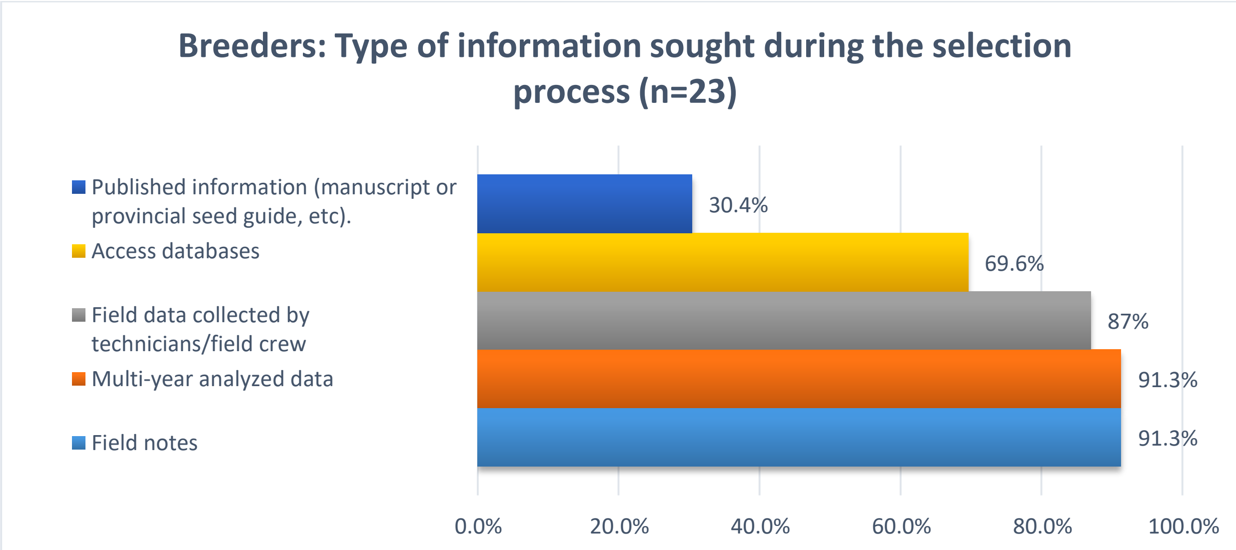
Figure 14. Seeking information during the breeding process – bioinfo/IT



The following question asked breeders what type of information breeders regularly look up when they make selection decisions during the plant breeding process (Figure 15). 'Field notes' and 'multi-year analyzed data' were equally ranked and preferred by almost all respondents (91.3%). The 'field data collected by technicians and field crew' option was also favoured by most of the respondents (87%), while the 'access databases' option was chosen by 69.6% of the breeders and plant breeders assistants. One third of the breeders (30.4%) consult 'public, analyzed data' information such a manuscript or a provincial seed guide.

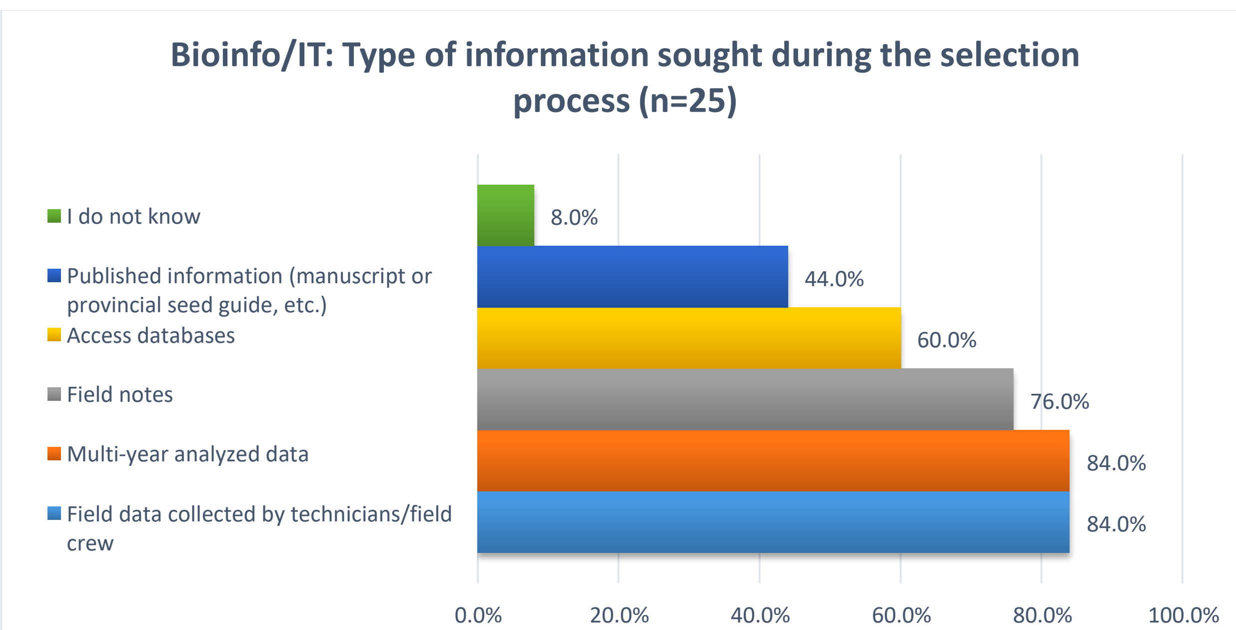
Four breeders or breeders' assistants added comments to this question. One of them wanted to clarify that they are seeking information from all the options presented as well as '*marker work (disease and herbicide)*'. Other answers included consulting '*genotyping data*', or a '*database with most of the above information*'. Another breeder added they need to '*consult with specialized scientists on the implications of highly technical results that require more intimate knowledge than I have*'.

Figure 15. Type of information sought during the selection process - breeders



When asked the same question, bioinformaticians ranked the type of information sought during the selection process similarly to breeders. Figure 16 indicates that the most preferred options were 'field data collected by technicians/field crew' (84%) and 'multi-year analyzed data' (84%), and, with a very small percentage difference, consulting 'field notes' (76%). 'Access databases' and 'published information such as manuscript or provincial seed guide' were chosen by 60% and, respectively, 44% of the bioinformaticians. A few respondents (8%) admitted that they do not know the type of information sought by breeders.

Figure 16. Type of information sought during the selection process – bioinfo/IT



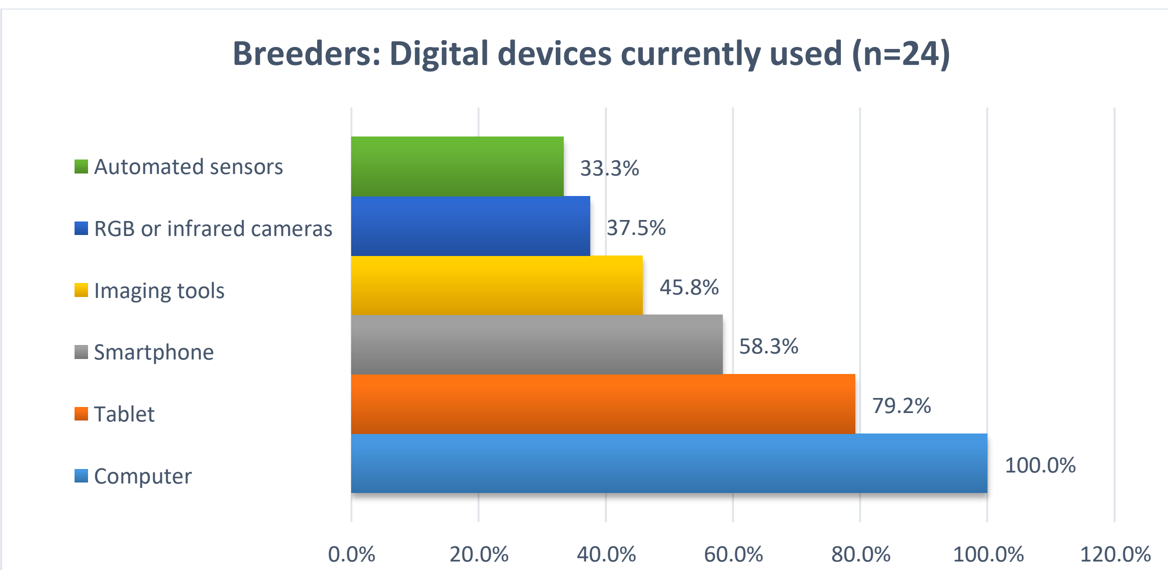
The next question was intended to explore whether breeders are overwhelmed with the amount of information presented to them by their breeding team members and collaborators during the plant breeding work. Out of 24 breeders who answered this question, most of them (91.7%) stated that they do not feel that too much information is presented to them, while 8.3% felt the opposite.

The same question about whether breeders are being presented with too much information by their team members or collaborators was addressed to bioinformaticians and IT developers. Out of the 25 respondents, 48% indicated that they do not know, 40% do not think breeders are presented with too much information and 12% believe the opposite.

9. Digital devices and databases usage

The next section of the survey focused on digital devices and databases usage. Breeders were asked what digital devices they are currently using in their breeding program, both indoor and in the field. All breeders indicated the 'computer' (100%) and most of them the 'tablet' (79.2%) (Figure 17). A majority of the respondents also use their 'phone' (58.3%) and slightly less than half of the respondents use 'imaging tools'. 'RGB or infrared cameras' (37.5%) as well as 'automated sensors' (33.3%) were selected by respondents. Besides the choices presented, breeders and plant breeders added in the Comments section that they are also using *drones, weather stations, handheld NIR*[1]*, colorimeters, optical sorter, digital voice recorder, barcode readers, Arduino board*[2]*, and Remark OMR.*

Figure 17. Digital devices used in the breeding process both indoor and in the field - breeders



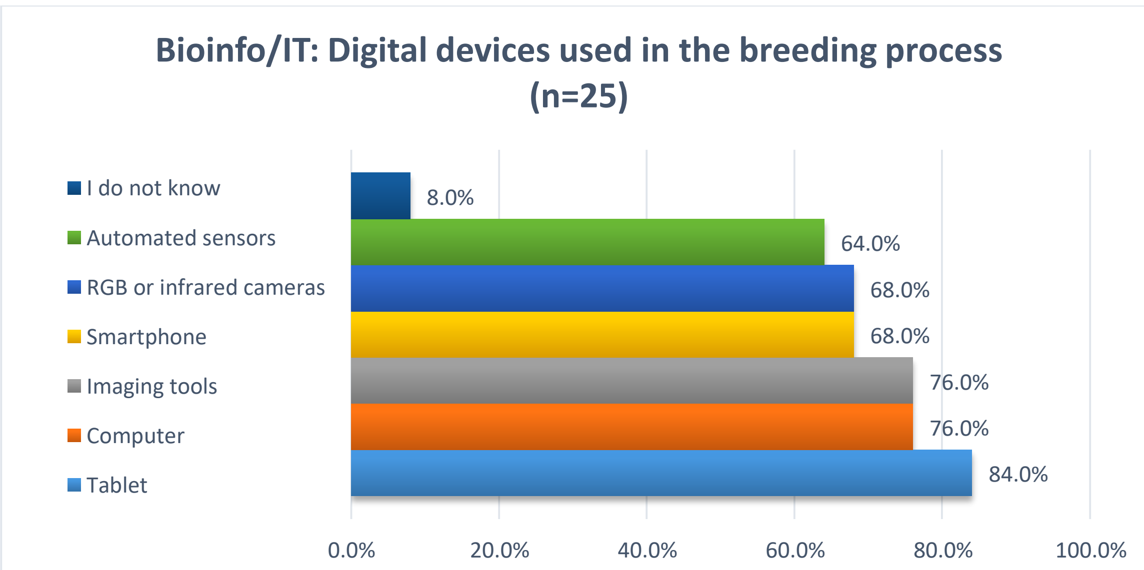
For the same question, most of bioinformaticians and IT developers' choices had reversed the rank of the first two options mostly preferred by breeders (Figure 18). They believe that breeders use the 'tablet' the most (84%), followed by the 'computer' (76%). The same happened with the next two

[1] Portable near-infrared (NIR) spectrometer
[2] Digital device used for automatic watering and data logging

ranked digital devices: bioinformaticians believe breeders use 'imaging tools' (76%) slightly more than 'smartphones' (68%). Further, while only one third of the breeders acknowledged using 'RGB or infrared cameras' and 'automated sensors', IT developers thought that the majority of the breeders are employing these devices (68% and, respectively 64%). Out of the 25 respondents to this question, 8% indicated that they do not know what digital devices breeders currently use in their breeding program, either indoor or in the field.

In summary, the difference between the two groups of responses is that bioinformaticians and IT developers believe that breeders and plant breeders' assistants employ certain digital devices to a higher degree than breeders indicate that they use. Few examples are imaging tools (76% of bioinformaticians versus 45.8% of breeders), automated sensors (64% versus 33.3%), RGB or infrared cameras (68% versus 37.5%).

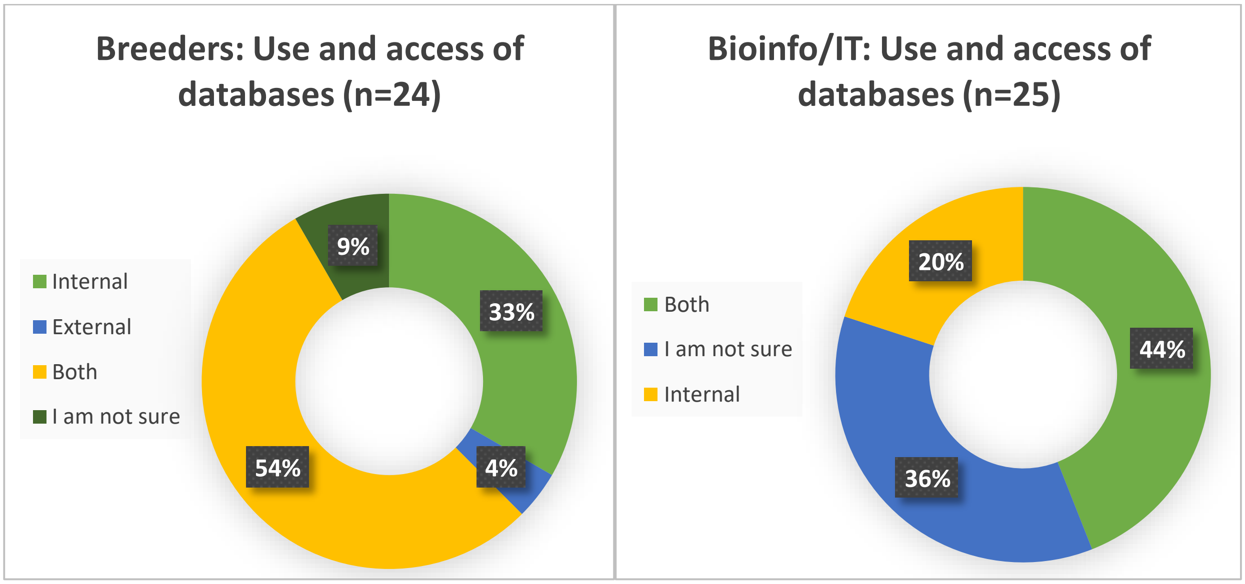
Figure 18. Digital devices used in the breeding process both indoor and in the field – bioinfo/IT



The next question asked respondents if they use or access any database in their breeding work (Figure 19). A majority of breeders and breeders' assistants (54%) use both internal and external databases, one-third use only internal databases, 9% are not sure, and 4% use mainly external databases.

Bioinformaticians and IT developers believe that breeders access both internal and external databases (44%), and internal databases (20%). More than a third of bioinformaticians (36%) indicated that they are not sure what kind of databases breeders use in their breeding work.

Figure 19. Databases usage



Next we asked breeders to share with us three databases that come to mind. Table 4 illustrates the answers of the sixteen breeders who answered this question. *The first database* mentioned by 9 of the breeders and breeders' assistants was their own their internal database. The other databases mentioned were Genesys (gene bank collection), GoBeans (plant genome database), CIERA (Crop Information Engine and Research assistant), Sunflower Genome database, PotatoBase (phenotyping and breeding database), CABI (Plant Genesis and Breeding database; germplasm profiling) and ICIS (International Crop Information Systems; information on crop improvement and management).

Nine respondents included a *second database* that came to their mind, including: KnowPulse (phenotypic and genotypic webportal and database), PGDC (Prairie Grain Development Committee; forum for information exchange), Ensembl (genome browser), Phytozome (Plant Comparative Genomics portal), internal database, GrainGenes (molecular and phenotypic information), Heliagene (sunflower genome and transcriptomes database), Sol Genomics (Solanaceae genomics network), and Breedbase (breeding management system).

Eight breeders mentioned a *third database* that came to their mind. These included: a cooperative testing database, GrainGenes (molecular and phenotypic information), NCBI (National Centre for Biotechnology Information), internal, Komugi (wheat genetic resources database), USDA GRIN (germplasm resources information network), Tomato Genetics Resource Centre and Sol Genomics (Solanaceae genomics network).

Reviewing the above, breeders' answers indicate the critical role of their own internal database, as mentioned by 11 respondents in total. As expected, breeders and breeders' assistants mentioned a wide range of databases, although everyone is mainly working on their specialty crop. The databases range from gene bank collections, genome databases, germplasm, phenotyping, genotyping to breeding databases.

Table 4. Three databases mentioned by breeders

Database 1	No. of responses	Database 2	No. of responses	Database 3	No. of responses
Internal database	9	**Knowpulse**	1	**Cooperative testing database**	1
Genesis	1	**PGDC (grain)**	1	**GrainGenes**	1
GoBeans	1	**Ensembl**	1	**NCBI**	1
CIERA	1	**Phytozome**	1	***Internal database***	1
Sunflower genome	1	***Internal database***	1	**Komugi**	1
PotatoBase	1	**GrainGenes**	1	**USDA GRIN**	
CABI	1	**Heliagene**	1	**Tomato Genetics Resource Centre**	1
ICIS	1	**Sol Genomics**	1	**Sol Genomics**	1
		BreedBase	1		

Bioinformaticians and IT developers were asked to tell us three databases that they think plant breeders are most aware of. As Table 5 illustrates, 11 bioinformaticians answered this question. Among the databases *first* mentioned, five bioinformaticians identified KnowPulse (phenotypic and genotypic webportal and database), and two of them mentioned Agronomix (plant breeding and variety testing software). Other databases mentioned were BrAPI (project that enables interoperability among plant breeding databases), USDA GRIN (germplasm resources information network), IBP (Integrated Breeding Platform; it enables sharing breeding knowledge), and PlotVision (software using the latest precision agriculture technology).

Agronomix was mentioned again by two respondents for the *second* database identified by bioinformaticians, followed by the Triticeae Toolbox (webportal containing phenotypic and pedigree data), Genesys (gene bank collection), internal database, USDA GRIN (germplasm resources information network), and NCBI (National Centre for Biotechnology Information). KnowPulse and PlotVision (software using the latest precision agriculture technology) were mentioned as the *third* database.

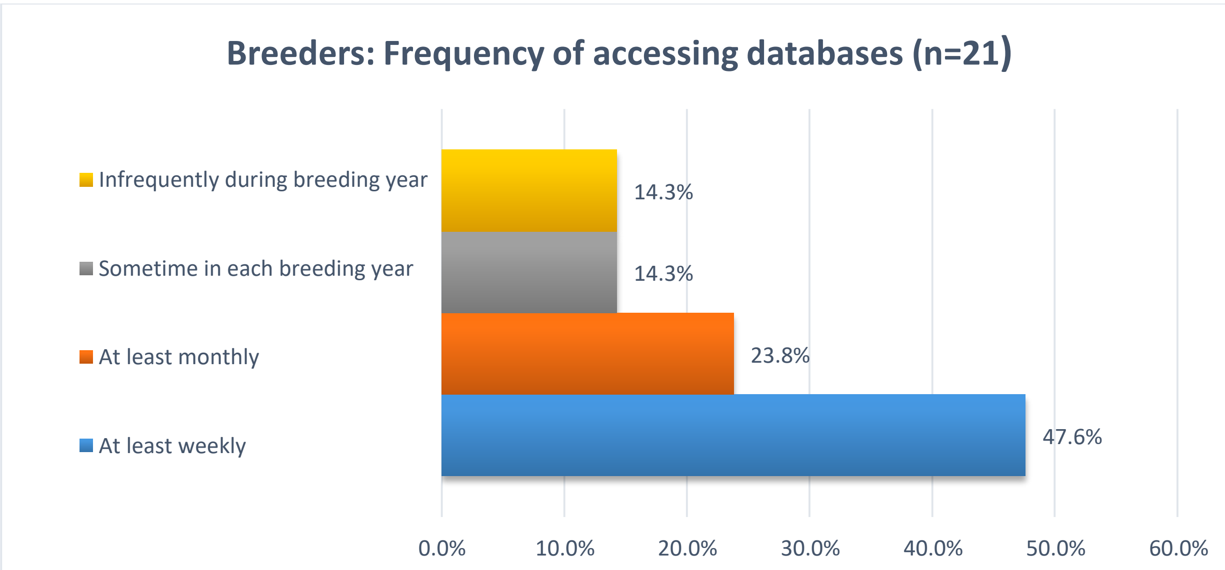
Table 5. Three databases that bioinformaticians think breeders are most aware about

Database 1	No. of responses	Database 2	No. of responses	Database 3	No. of responses
KnowPulse	5	**Agronomix (AgroBase)**	2	**KnowPulse**	1
Agronomix (AgroBase)	2	**Triticeae Toolbox**	1	**PlotVision**	1
BrAPI	1	**Genesys**	1		
USDA GRIN	1	**Internal database**	1		
IBP	1	**USDA GRIN**	1		
PlotVision	1	**NCBI**	1		

Comparing breeders and bioinformaticians' answers (16 versus 11 respondents), it was surprising that only one bioinformatician identified the usage of internal databases. This result could have two interpretations. First, bioinformaticians have named the databases by their given name and may not identified it as 'internal database'. The second interpretation would suggest that bioinformaticians are not aware about the importance of internal databases for breeders. Correlating these responses with those shown on Figure 19 ('Databases usage'), the second interpretation appears more likely.

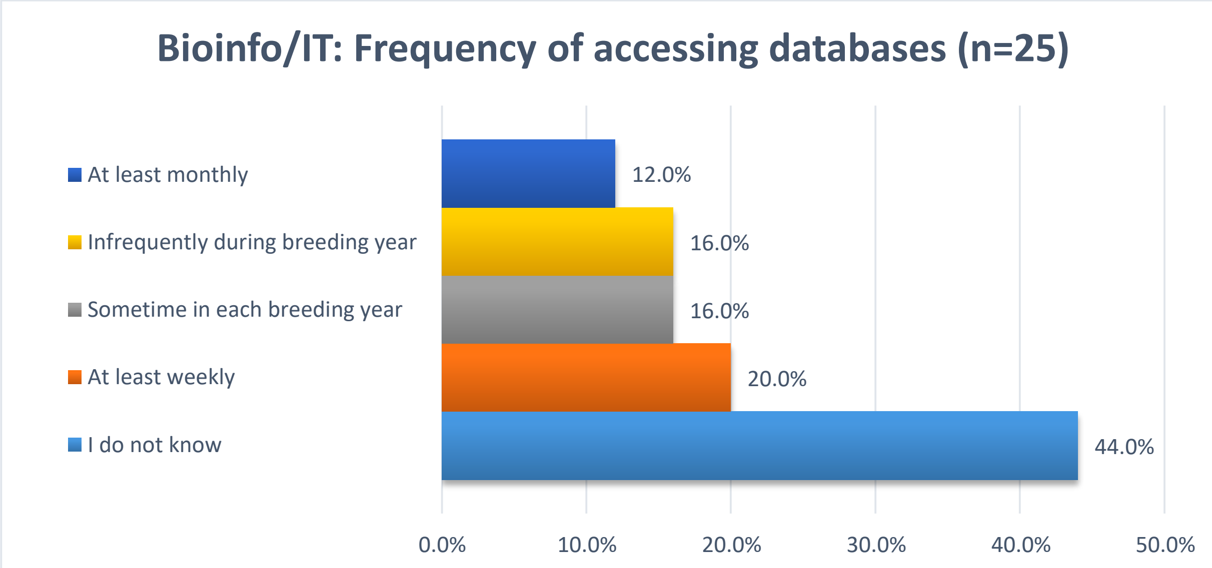
Next we asked breeders how often they access a database during the plant breeding process. Figure 20 indicates that almost half of the breeders answered that they access a database at least weekly (47.6%), and almost a quarter of them (23.8%) access it at least monthly. Few breeders said they access it only sometimes in each breeding year (14.3%) or infrequently during the breeding year (14.3%).

Figure 20. Frequency of accessing databases - breeders



Almost half of the bioinformaticians and IT developers (44%) stated that they do not know the frequency with which breeders access the database during breeding process (Figure 21). Further, 20% of the respondents believe breeders access a database 'at least weekly', 16% 'sometimes in each breeding year' and 'infrequently during the breeding year. Only 12% of them think breeders access a database at least monthly.

Figure 21. Frequency of accessing databases – bioinfo/IT



Again, there are some discrepancies between breeders and bioinformaticians' answers with regards to database' access frequency. Frequent use of a database that contains large amount of data is time consuming as formulating queries or obtaining the desired result can be frustrating for the user. This piece of information is important for the bioinformatician or IT developer who works in developing functional database, both internal or external.

10. Usage and types of omics

The next section of the survey contained questions about omics (Figure 22). First, breeders were asked whether they are familiar with the term 'omics', and almost all of them (95.8% of 24 respondents to this question) answered affirmatively.

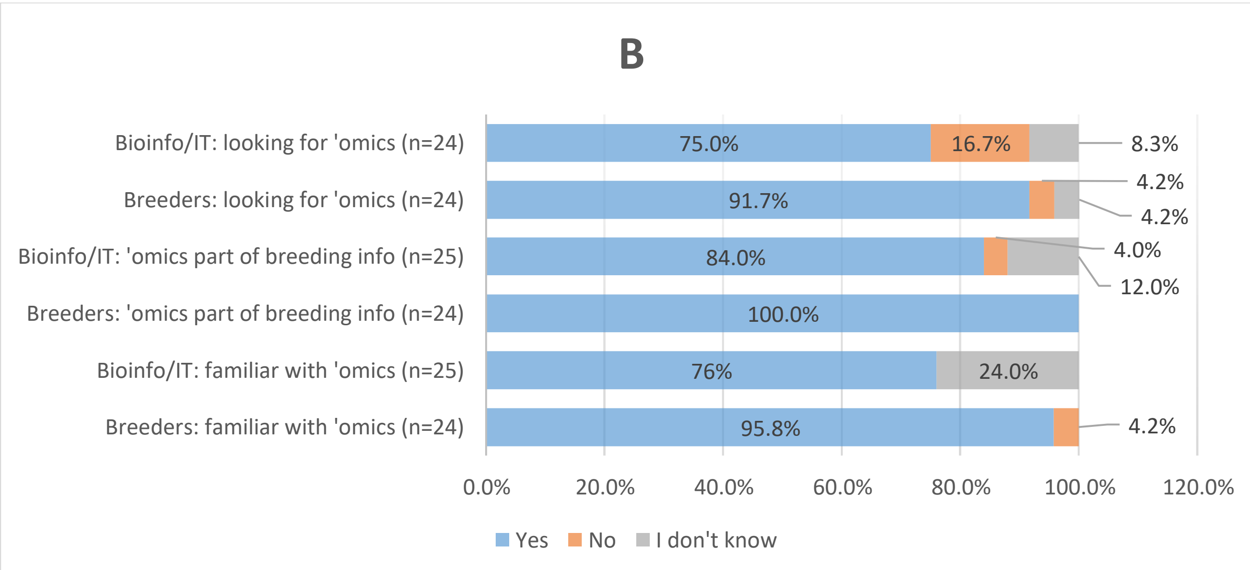
Next, the following definition of 'omics was prompted to respondents: *"omics could be defined as a collective characterization and quantification of biological molecules, which includes but not limited to genomics, transcriptomics, proteomics, phenomics and metabolomics".* Further, breeders were asked whether omics data is considered part of breeding information and all 24 respondents answered positively.

When bioinformaticians were asked whether they think breeders are familiar with the term 'omics, three quarters of the 25 respondents to this question (76%) gave a positive response. The rest of 24% indicated that they do not know. Further, when presented with the same definition and asked if they think breeders consider 'omics data as part of their breeding information, 84% of the 25 respondents answered affirmatively, 12% said that they do not know and 4% answered negatively.

The following question asked breeders whether they are looking for 'omics information during the plant breeding process. Almost all breeders (91.7% of 24 respondents) stated that they are looking for this type of data, while 4.2% denied the need and 4.2% answered that they do not know.

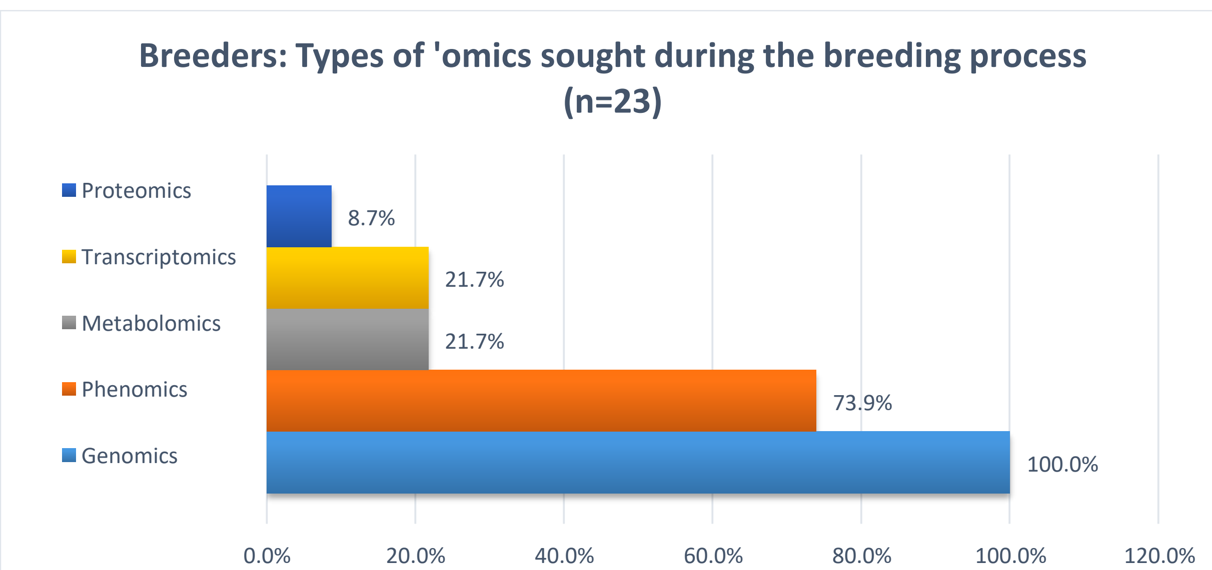
At the same time, bioinformaticians were asked if, in their opinion, breeders look for ‘omics information during the breeding process. Three quarters (75%) of the 24 respondents believe breeders look for ‘omics information, while 16.7% do not know and 8.3% offered a negative answer.

Figure 22. Breeders' and bioinfo/IT knowledge of and familiarity with 'omics



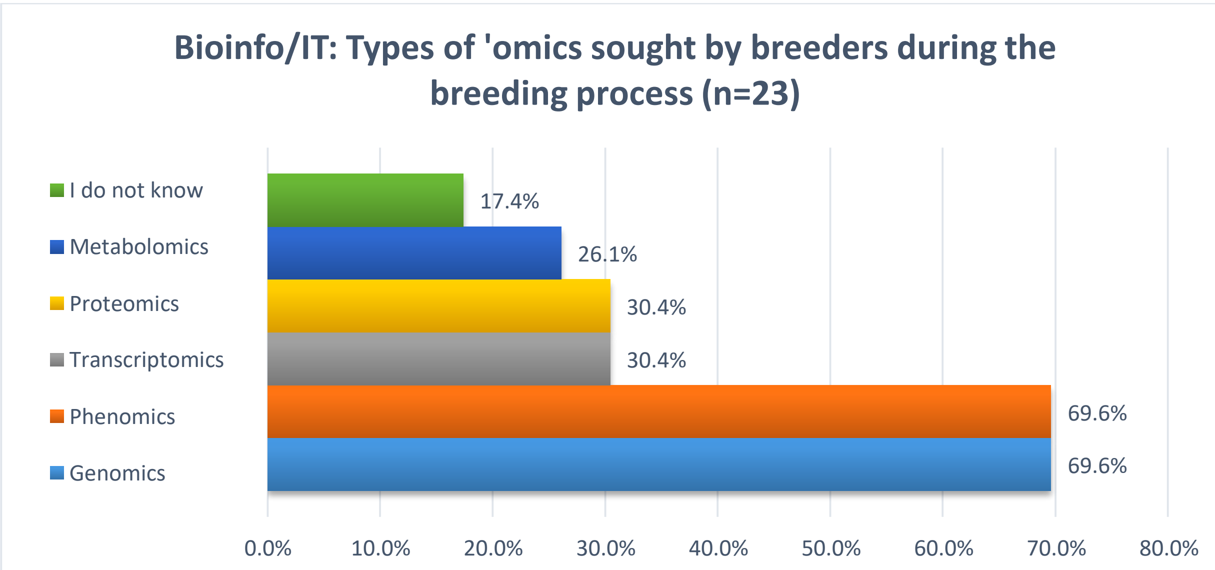
Subsequently, the breeders who answered that they are looking for ‘omics during the breeding process, were asked what types of ‘omics they are looking for during the breeding process and were invited to select all applicable options. Figure 23 shows that all breeders look for genomics and three quarters of them look for phenomics (73.9%). Fewer breeders look for metabolomics and transcriptomics (21.7%) and only 8.7% look for proteomics.

Figure 23. Types of ‘omics - breeders



Similarly, bioinformaticians were asked what sort of 'omics they think breeders look for during the breeding process (Figure 24). The largest share of responses pointed toward genomics and phenomics (69.6%). The rest of the options were transcriptomics and proteomics (both 30.4%), and metabolomics (26.1%). Of the 23 respondents to this question, 17.4% were not aware of the types of omics breeders seek during the breeding process.

Figure 24. Types of 'omics – bioinfo/IT



We also asked breeders their opinion on various related 'omics matters. These questions on 'omics were developed as recent advances in the 'omics research has led to a dramatic growth in technologies available to the breeders. The availability of various 'omics data sets should theoretically provide them with a more comprehensive information relating to their crop species. However, big data generated by various novel technologies brings the challenge of actually using it and transforming it into decision-relevant knowledge. As this is a topic related to breeders' profession and expertise, bioinformaticians were not asked these questions.

As shown in Table 6, breeders had to evaluate each statement as true or false. This survey research technique, using multiple-true-false questions that have a common stem topic ('omics in our case), has the advantage of obtaining a quick description on the usage and knowledge of 'omics. The questions were structured following the UTAUT model, developed by Venkatesh et al., (2003). The UTAUT model facilitates determining users' behavioural intention to use a technology. Among other factors, the model has four main components: performance expectancy, effort expectancy, social influence and facilitating conditions. Thus, the questions were designed to attain an indication of breeders' intention to use 'omics.

Breeders' responses show that 'omics usage enables most of them (78.3%) to accomplish work tasks more quickly and also increases their productivity (78.3%). Further, all breeders (100%) agreed that 'using 'omics neither hamper their performance nor the quality of their work' (95.7%).

With regards to the ease of obtaining the needed ‘omics data, two third of the breeders (68.2%) do not find it easy to obtain ‘omics data and three quarters (73.9%) of them do not find it easy to extract the information from the ‘omics data. However, a majority of breeders believe that using ‘omics does not take too much time from their normal duties. Perhaps this why almost all respondents support using ‘omics data (95.5%) and encourage others to use ‘omics data in their work (86.4%).

Next, breeders were asked whether using ‘omics is a status symbol in their work, and one third of them answered affirmatively. Further, 71.4% acknowledged that they have the knowledge necessary to handle ‘omics data. However, one third of the breeders (33.3%) indicated that the ‘omics data format is not compatible with other systems they are currently using, and they can’t access in-person technical support when having difficulties with omics data (28.3%). However, when asked if, when having difficulties handling omics data, they can find supporting resources and documentation by accessing available information on the internet, 61.9% said yes.

Most of the breeders (71.4%) acknowledged that they do not feel apprehensive about using ‘omics data and all breeders admitted that they trust ‘omics data. Nevertheless, close to third (28.6%) of the breeders agreed that ‘omics data give a lot of information that is not relevant to them and not what they need, and a few breeders (15%) admitted that they are confused with the various outcomes from various data queries when trying to find out more information on ‘omics.

Summarizing this set of questions, it can be noted that 70 to 80 percent of the breeders believe that ‘omics usage increases their productivity and enables faster accomplishment of tasks. However, even though using omics does not take too much time from the breeders’ normal duties, it seems that finding the needed ‘omics and extracting the information from the ‘omics data are not seen as easy tasks. For approximately a third of the breeders, the data format is incompatible with the current systems in use, and they have difficulty getting technical support when having issues with ‘omics data. The answers provided for this set of questions indicate majority of respondents have the behavioral intention of using ‘omics in their work.

Table 6. Breeders’ opinions on the usage of ‘omics

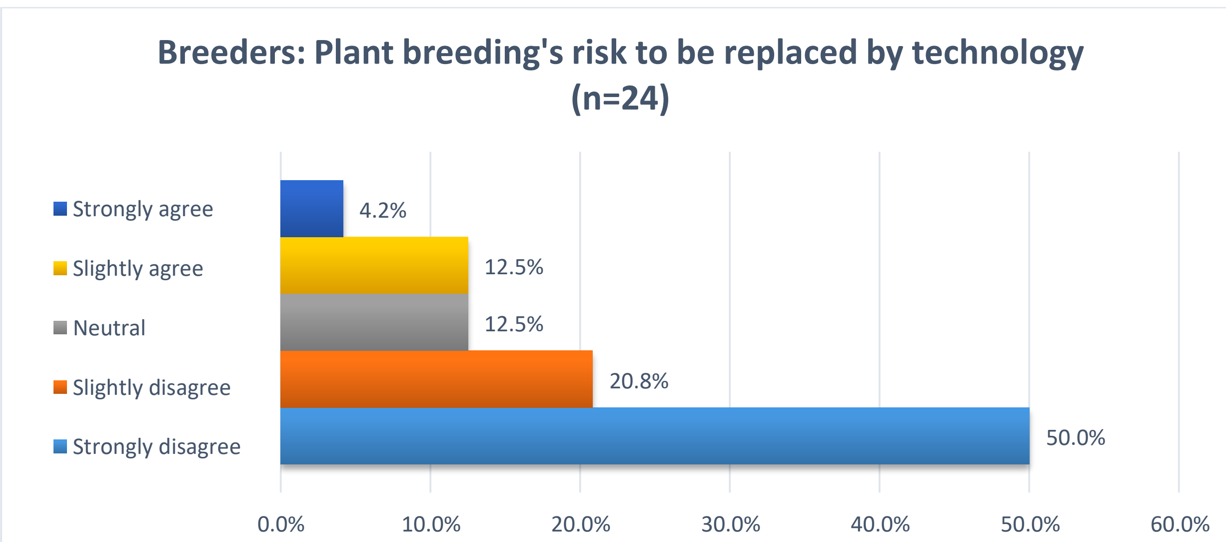
Statement	True (%)	False (%)
Using ‘omics in my work enables me to accomplish tasks more quickly. (n=23)	78.3	21.7
Using ‘omics in my work hampers my performance. (n=23)	0	100
Using ‘omics in my work increases my productivity. (n=23)	78.3	21.7
Using ‘omics in my work hampers the quality of the work I do. (n=23)	4.3	95.7
I find it easy to obtain the ‘omics data I need. (n=22)	31.8	68.2
I find it easy to extract the information from the ‘omics data. (n=23)	26.1	73.9
Using ‘omics takes too much time from my normal duties. (n=22)	27.3	72.7
I am indifferent about using ‘omics data. (n=22)	4.5	95.5
I encourage others to use the ‘omics data in their work. (n=22)	86.4	13.6
Using ‘omics is a status symbol in my workplace. (n=21)	33.3	67.7
I have the knowledge necessary to use ‘omics data. (n=21)	71.4	28.6
The ‘omics data format is not compatible with other systems I am currently using. (n=21)	33.3	67.7

I cannot access in-person technical support when I am having difficulties with 'omics data. (n=21)	28.6	71.4
When I am having difficulties handling the 'omics data, I can find supporting resources and documentations by accessing available information the websites or on internet. (n=21)	61.9	38.1
I feel apprehensive about using 'omics data. (n=21)	28.6	71.4
'omics data tend to give me a lot of information that is not relevant to me or not what I need. (n=21)	28.6	71.4
I do not trust 'omics data. (n=21)	0	100
I am confused with the various outcomes from various data queries when trying to find out more information on 'omics. (n=20)	15	85

11. Plant breeding's risk of being replaced by technology

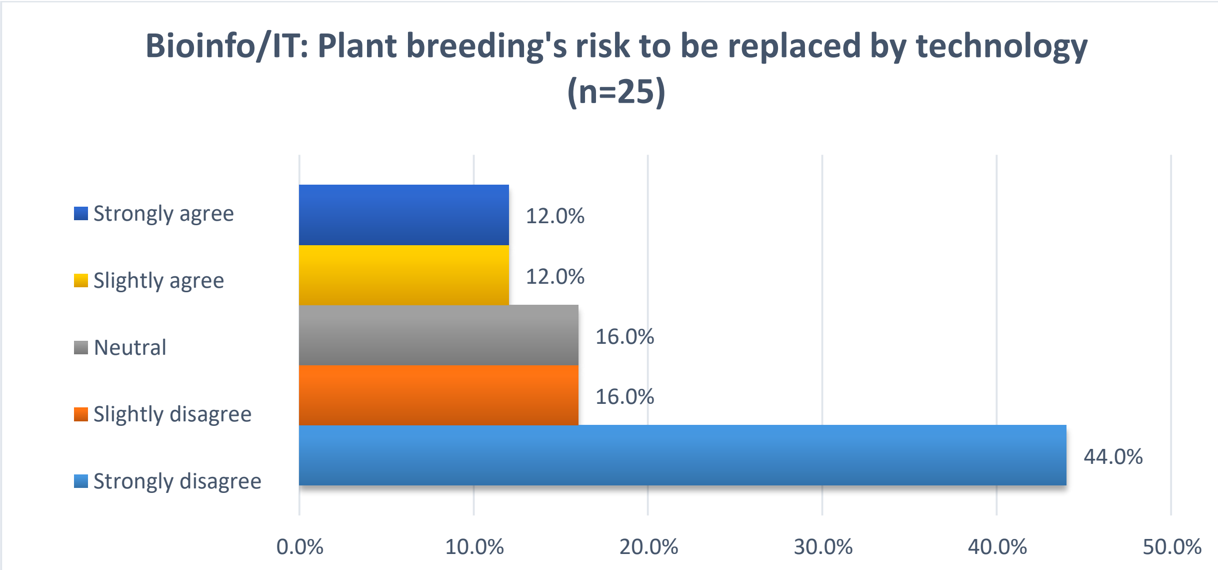
Next, breeders were asked whether plant breeding is at risk of being replaced by technology. As shown on Figure 25, half of them (50%) strongly disagreed, 20% slightly disagreed, 12.5% were neutral and 12.5% slightly agreed. Out of the 24 respondents, 4.2% strongly agreed to the question.

Figure 25. Plant breeding to be replaced by technology - breeders



For this question, bioinformaticians and IT developers were asked about their own opinion of whether they think plant breeding is at risk of being replaced by technology. A little less than half strongly disagree (44%) and 16% slightly disagree (Figure 26). Sixteen percent chose the neutral answer, while the rest of the bioinformaticians' answers are equally distributed between slightly agree (12%) and strongly agree (12%).

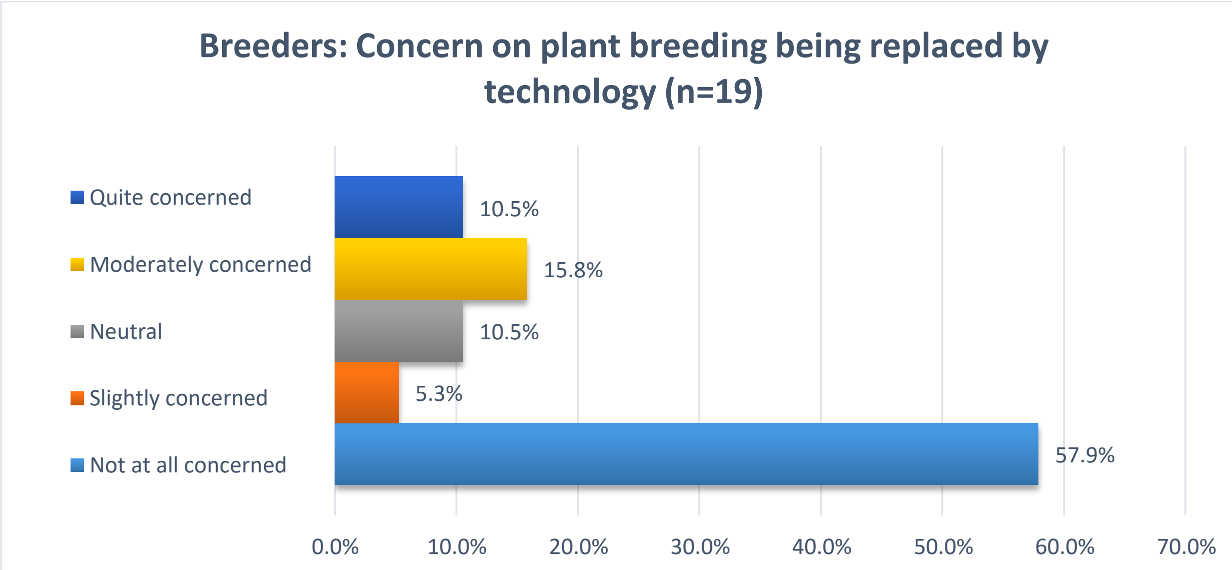
Figure 26. Plant breeding to be replaced by technology – bionfo/IT



To compare the answers of breeders and bioinformaticians, we combined the statements ‘strongly agree’ and ‘slightly agree’, and we observe that fewer breeders (16.7%) than bioinformaticians (24%) think that plant breeding is at risk to be replaced by technology. Conversely, when adding up the percentages for ‘strongly disagree’ and ‘slightly disagree’, more breeders (70.8%) than bioinformaticians (60%) disagree that plant breeding is at risk of being replaced by technology. The small percentage difference indicates that the answers of the two categories of respondents are similar.

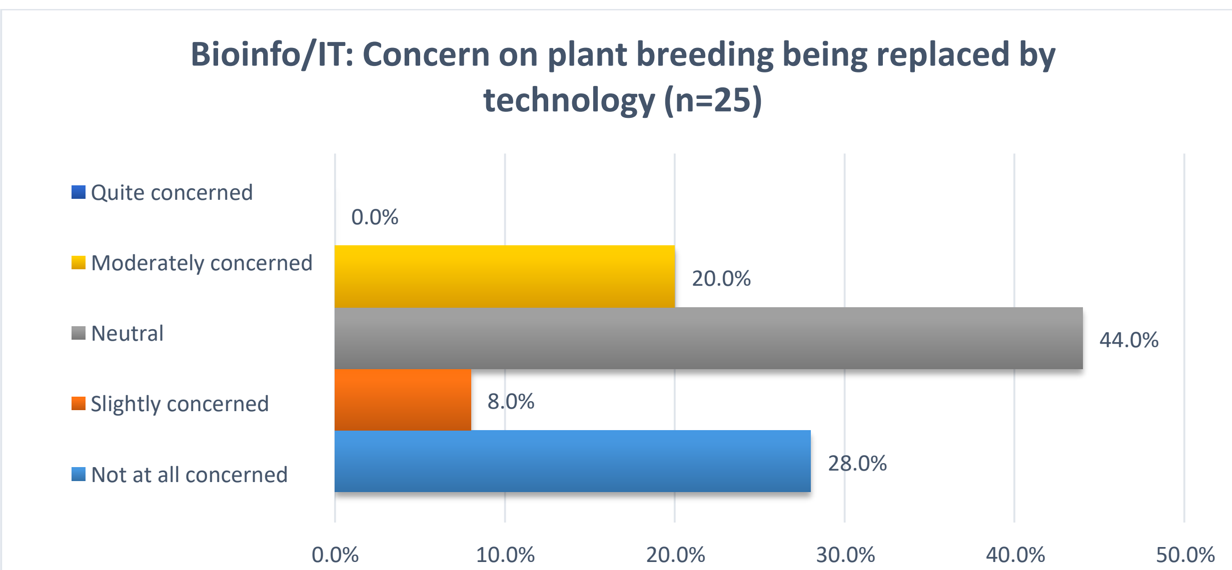
The next question was intended to assess breeders’ level of concern that plant breeding is at risk of being replaced by technology (Figure 27). Thus, breeders were asked if they consider that plant breeding is at risk of being replaced by technology, to share with us their level of concern. A majority of breeders (57.9%) are not at all concerned and only 5.3% are slightly concerned. Breeders who are quite concerned (10.5%) and moderately concerned (15%) represent a quarter of all respondents.

Figure 27. Level of concern about plant breeding to be replaced by technology – breeders



In turn, bioinformaticians were asked what they think is a breeders' level of concern about plant breeding being replaced by technology. Figure 28 illustrates that bioinformaticians and IT developers believe that 28% of the breeders are not at all concerned and only 8% are slightly concerned. They think that 44% of the breeders are neutral on this issue. None of them consider that breeders would be quite concerned and only 20% believe that breeders are moderately concerned.

Figure 28. Level of concern about plant breeding to be replaced by technology – bioinfo/IT



A quick assessment of breeders and bioinformaticians' answers shows that the only notable difference is that while bioinformaticians think that majority of breeders are neutral or slightly concerned, breeders' answers indicate that they not concerned at all.

12. The one thing that would improve breeding programs

Breeders were asked what would be one thing that they would like to improve in their breeding program. As expected, the range of answers was quite diverse, however, the most mentioned topic was the need for funding or financial support and stability (Table 7). Automation in phenotyping and data integration were mentioned a couple of times as well. While faster processing of databases and better bioinformatics support were considered important, one respondent highlighted his/her awareness of the need for more bioinformatics and artificial intelligence knowledge than what she/he currently has to be able to keep up with genomics and bioinformatics.

Table 7. Breeders': the one thing they would like to improve in their plant breeding cycle (n=19)

Communication
Financial support and stability
Access to HQP *[highly qualified personnel]*
Funding!
IoT data acquisition, automation in phenotyping *[IoT - Internet of Things - the network of computing devices and the technology that facilitates communication between devices, and between cloud and devices]*
Access to traits
Automation in phenotyping, feedback from industry
Data integration
Greater opportunity to provide thought leadership with industry around innovations coming/planned in my breeding pipeline
Better bioinformatics support
High throughput phenomics
More consistent financial support
I feel like I'm having a hard time keeping up with everything in genomics and bioinformatics. It seems like I need a little more bioinformatics knowledge than what I have. I also feel like I need to learn more about Artificial Intelligence and its applications in plant breeding.
Reduce labour requirements / increase mechanization and automation of tasks
More database on allogamous perennial species
Data integration
Some data collection with drones (canopy cover, maturity date)
Faster processing of data bases and faster computers in general
Implementation of more KASP (or similar) markers for key traits

Further, bioinformaticians were asked to share with us what is the one improvement that could be introduced to improve the plant breeding cycle (Table 8). Many suggestions converged towards data collection automation, better organization of historical data, better software and databases tools and technology uptake that would organize, connect and summarize breeding data. One bioinformatician highlighted breeders' need for practical bioinformatics training. Another respondent detailed the need for faster adoption of new technologies in plant breeding programs, in particular for new 'omics technologies because of the huge volumes of data generated and data analysis needed.

Table 8. Bioinformaticians' suggestions for improving the plant breeding cycle (n=11)

Automation of data collection and analysis.
Better organization of historical data
Practical, biology-based bioinformatics training
A faster adoption cycle of new technology in plant breeding programs would be beneficial. This is particularly true for the new omics technologies, but it has to be remembered that there are still particular challenges in doing this, as there are still issues with the huge volumes of data generation and data analysis required. So you have to expect adoption of omics technologies to be phased in at different times, with variation between different crops, to accommodate an efficient introduction of the technologies into long term breeding programs.
Uptake of technology to better organize and make connections between breeding data
Remove whatever the current bottleneck is - will vary between programs, and crops.
More database tools to summarize complex data to provide a quick overview in the field
Genomic selection; gene editing
More field assistance
Easy to access information for breeders
Better software tools

The last question of the survey invited respondents to share with us anything related to the survey topic that they think it is important (Table 9). One breeder expressed his/her concern about the future plant breeding.

Table 9. Breeders' thoughts on the survey topic (n=6)

I got the sense from the survey the emphasis was on having breeding material already available to select. Which is the largest time commitment in breeding, but breeding also involves things such as researching parental germplasm, planning crosses, and introducing new technology (that includes not only 'omics' but field agronomy and equipment, lab equipment, software etc.) that may not take as much time as steps in the selection process but are critically important to the success of breeding.
Thank you for conducting the survey. It is important to address these issues in a fast changing work landscape for plant breeders.
I do think a lot about CRISPR-Cas9 and related technologies, and increasing knowledge connecting nucleic acid sequences with function and phenotype, and the idea that these technologies can replace the need for plant gene banks - and possibly for plant breeding as well. At the moment I remain optimistic that plant breeding has a role into the future. As plant breeders we deliver an entire "package" of traits for functionality along the entire value-chain from field to fork, for the industry served
Check out CGIAR's Excellence in Breeding Platform
This was interesting and thought-provoking - thanks!
It has been interesting, thanks.

On the same topic (Table 10), one bioinformatician restated the need for bioinformatics training for breeders, and the other two shared their view on plant breeding and the uptake of new technology.

Table 10. Bioinformaticians' thoughts on the survey topic (n=3)

Practical, biology-based bioinformatics training is extremely limited at USask.
With respect to the issue of concern that new technologies will replace plant breeding. The fact of the matter is that the new technology only allows us to expedite the breeding process - the essence of plant breeding in terms of the physical processes involved has to remain the same because its dependent on the fundamentals of plant biology, genetics and physiology that define how plant/crops are bred. The technologies that go into the 'breeders toolbox' and help speed up the process is vital of course - it essentially allow breeders to do more in the same time which is important with a changing climate where environmental conditions are more variable. In my experience breeders are keen adopters of new technology when its apparent it has benefits to their programs. They are not concerned about it as something that will replace them anytime soon - it will not, but they are concerned that the narrative that new technologies can now replace breeders completely is taken seriously, particularly from exponents with little or no direct experience in plant breeding.
Plant breeders seem to be very divided on their use of technology. It seems that some embrace it as a tool to inform their decisions and others don't feel the tools exist catering to them.

13. Questionnaires and consent form

1. What is your current position?
   a. Plant breeder
   b. Plant breeder assistant
   c. Bioinformatician
   d. IT developer
   e. Other

2. What is your current workplace?
   a. Academia
   b. Government research facility
   c. Private research facility
   d. Other

3. What is the highest level of education have you completed?
   a. Some or all of an undergraduate degree and/or technical diploma
   b. Master's degree
   c. PhD
   d. Other (Please specify)

4. For how many years have you been working in your current field?
   a. less than 10 years;
   b. 10-25 years;
   c. More than 25 years;

Breeders	**IT developers**
5. How are your breeding priorities being determined? Please choose all that apply. a. Told by your supervisor/director b. Explicit requirements from industry partners c. Perceived industry needs d. Determined personally e. All of the above f. Other	5. In your opinion, how are breeding priorities being determined for plant breeders? Please choose all that apply. a. Told by their supervisor/director b. Explicit requirements from industry partners c. Perceived industry needs d. Determined personally e. All of the above f. I do not know g. Other
6. In your opinion, is plant breeding primarily driven by the breeder or is it a team effort? a. Breeder-led b. Team effort c. I do not know d. Other	6. In your opinion, is plant breeding primarily driven by the breeder or is it a team effort? a. Breeder-led b. Team effort c. I do not know d. Other

7. In your opinion, what are the essential skills/competencies for a plant breeder? Please choose all that apply. Further, please rank your first 3 options in order of importance, from 1 to 3 where 1 is the most important. "Other" category can be included in the ranking: a. Education (PhD, plant breeding training course) b. Hands-on experience with the plant c. Experience with the industry sector d. Knowledge of latest technological development e. Experience with farm machinery operation f. Statistical and data analysis g. Physical abilities h. I do not know i. Other	*7*. In your opinion, what are the essential skills/competencies for a plant breeder? Please choose all that apply. Further, please rank your first 3 options in order of importance, from 1 to 3 where 1 is the most important. "Other" category can be included in the ranking: a. Education (PhD, plant breeding training course) b. Hands-on experience with the plant c. Experience with the industry sector d. Knowledge of latest technological development e. Experience with farm machinery operation f. Statistical and data analysis g. Physical abilities h. I do not know i. Other
8. During the plant breeding process, how is the breeding information recorded and communicated? (Please choose all that apply) a. Any piece of paper b. Notebook c. Smartphone d. Tablet e. Computer f. Email g. Video or voice recording h. An online portal/database i. An open, sharable excel spreadsheet j. Other	8. During the plant breeding process, do you know how breeding information is being recorded and communicated? (Please choose all that apply) a. Any piece of paper b. Notebook c. Smartphone d. Tablet e. Computer f. Email g. Video or voice recording h. An online portal/database i. An open, sharable excel spreadsheet j. I do not know k. Other
9. Are you happy about how the information is captured and communicated to you during the plant breeding process? a. Yes b. No c. Other	9. Do you think plant breeders are happy about how the information is captured and communicated to them during the plant breeding process? a. Yes b. No c. I do not know d. Other
10. If No, do you have a ***brief*** suggestion for improvement with regards to how you would prefer to have the information presented to you? (Open ended)	10. If No, do you have a ***brief*** suggestion for improvement with regards to how you think breeders would prefer to have the information presented to them? (Open ended)
11. When you need more information during the plant breeding process, how do you seek the information? Please choose all that apply.	11. When plant breeders need more information during the plant breeding process, how do you

a. Need to do some thinking/use my experience/intuition b. Go to the field/phytotron/greenhouse c. Chat with my technicians/field crew d. Access my field notes/raw data that is accessible only to me or to my team e. Access public, analysed data (e.g. internal field data, data from provincial seed guide) f. Access a database g. I do not know h. Other	think they seek the information? Please choose all that apply. a. Need to do some thinking/use their experience/intuition b. Go to the field/phytotron/greenhouse c. Chat with technicians/field crew d. Access field notes/raw data that is accessible only to them or their team e. Access public, analysed data (e.g. internal field data, data from provincial seed guide) f. Access a database g. I do not know h. Other
12. What would be the 3 to 5 type of information that you regularly look up when you make selection decisions during the plant breeding process? a. Field notes b. Field data collected by technicians/field crew c. Multi-year analyzed data d. Published information such as manuscript or provincial seed guide, etc. e. Access databases f. I do not know f. Other	12. What would be the 3 to 5 type of information that you think plant breeders regularly look up when they the make selection decisions during the plant breeding process? a. Field notes b. Field data collected by technicians/field crew c. Multi-year analyzed data d. Published information such as manuscript or provincial seed guide, etc. e. Access databases f. I do not know f. Other
13. Do you feel like too much information is being presented to you by your breeding team members and collaborators in your plant breeding work? a. Yes **b.** No **c.** I do not know	13. Do you feel like too much information is being presented to breeders by their breeding team members and collaborators in the plant breeding work? a. Yes **b.** No **c.** I do not know
14. During the plant breeding process, do you make all the executive decisions? a. Yes b. No c. Other	14. During the plant breeding process, do you think the breeder makes all executive decisions? a. Yes b. No c. I do not know d. Other
15. If Yes, during the plant breeding process, who else is involved in data quality control/decision-making process? *[Open]*	15. If Yes, during the plant breeding process, who else do you think is involved in data quality control/decision-making process? *[Open]*
16. Can you identify one thing that you would like to improve in your breeding program? *[Open]*	16. From your perspective, what is the one thing that needs to be improved within the breeding process/cycle? *[Open]*

17. What digital devices do you currently use in your breeding program (both indoor and in the field)? a. Computer b. Smartphone c. Tablet d. Automated sensors e. RGB or infrared cameras f. Imaging tools g. Other	17. In your opinion, what digital technology and other devices do breeders currently use both indoor and in the field? a. Computer b. Smartphone c. Tablet d. Automated sensors e. RGB or infrared cameras f. Imaging tools g. I do not know h. Other
18. What other digital devices do you use in your program?	18. In your opinion, what other digital devices do breeders use in their work?
19. Do you use/access any database (both internal and external) in your breeding work? a. internal b. external c. both d. I do not know	19. What type of database do you think breeders use/access (both internal and external) in their breeding work? a. internal b. external c. both d. I do not know
20. Can you tell us up to 3 databases that come to your mind?	20. Can you tell us up to 3 databases that you think plant breeders are most familiar with?
21. How often do you access a database during the plant breeding process? a. At least weekly b. At least monthly c. Sometime in each breeding year d. Infrequently during breeding year e. Other	21. How often do plant breeders access a database during the plant breeding process? a. At least weekly b. At least monthly c. Sometime in each breeding year d. Infrequently during breeding year e. I do not know f. Other
22. Are you familiar with the term 'omics? a. Yes b. No *Definition: collective characterization and quantification of biological molecules, which includes but not limited to genomics, transcriptomics, proteomics, phenomics, and metabolomics.*	22. Do you think breeders are familiar with the term 'omics? a. Yes b. No c. I do not know *Definition: collective characterization and quantification of biological molecules, which includes but not limited to genomics, transcriptomics, proteomics, phenomics, and metabolomics.* d. Yes e. No f. I do not know
23. Is 'omics data considered part of breeding information? a. Yes	23. Do you think breeders consider 'omics data as part of breeding information? a. Yes

b. No c. I do not know d. Other	b. No c. I do not know d. Other
24. Do you look for ‘omics information during the plant breeding process? a. Yes b. No c. I do not know d. Other	24. In your opinion, do breeders look for ‘omics information during the plant breeding process? a. Yes b. No c. I do not know d. Other
25. If Yes, what sort of ‘omics data do you typically look for? Please choose all that apply: a. Genomics b. Phenomics c. Other	25. If Yes, what sort of ‘omics do you think breeders typically look for? Please choose all that apply. a. Genomics b. Phenomics c. I do not know d. Other
26. To what extent do you agree with the following statement: Is plant breeding at risk of being replaced by technology? [1=Disagree, 7=Agree]	26. To what extent do you agree with the following statement: Is plant breeding at risk of being replaced by technology? [1=Disagree, 7=Agree]
27. IF SLIGHTLY AGREE AND UP: if you consider that plant breeding is at risk of being replaced by technology, please rank on a scale from 1 to 7 how much does that concern you?	27. IF SLIGHTLY AGREE AND UP, if you consider that plant breeding is at risk of being replaced by technology, please rank on a scale from 1 to 7 how much do you think plant breeders are concerned about this?

FOR BREEDERS ONLY

Please mark the following as either True or False:	**True**	**False**
Using ‘omics in my work enables me to accomplish tasks more quickly.		
Using ‘omics in my work hampers my performance.		
Using ‘omics in my work increases my productivity.		
Us an ‘omics in my work hampers the quality of the work I do.		
I find it easy to obtain the ‘omics data I need		
I find it easy to extract the information from the ‘omics data		
Using ‘omics takes too much time from my normal duties.		
I am indifferent about using ‘omics data		
I encourage others to use the ‘omics data in their work.		
Using ‘omics is a status symbol in my workplace.		
I have the knowledge necessary to use ‘omics data		
The ‘omics data format is not compatible with other systems I am currently using		

I cannot access in-person technical support when I am having difficulties with 'omics data		
When I am having difficulties handling the 'omics data, I can find supporting resources and documentations by accessing available information the websites or on internet		
I feel apprehensive about using 'omics data.		
'omics data tend to give me a lot of information that is not relevant to me or not what I need		
I do not trust 'omics data		
I am confused with the various outcomes from various data queries when trying to find out more information on 'omics		

Consent Form

ENHANCING THE VALUE OF LENTIL VARIATION FOR ECOSYSTEM SURVIVAL (EVOLVES).

Project leaders: Dr. Kirstin Bett and Dr. Bert Vandenberg

Summary of the Project:

The study in which you have been invited to participate is concerned with better understanding the uniquely and extremely complex plant breeding work-flow, as well as decision-making processes in the context of new technology uptake. Actual innovation implementation in plant breeding depends on the collaboration and cooperation work of plant breeders and IT developers. To be able to contribute to the development of this industry, we would like to document your knowledge, in your quality of highly specialized experts in your field, as you are constantly exposed to the challenges and rewards of plant breeding.

This project is led by Dr. Kirstin Bett and Dr. Bert Vandenberg. Dr. Peter Phillips is a Principal Investigator in this project. The name of the project is "Enhancing the Value of Lentil Variation for Ecosystem Survival" (EVOLVES) and it is funded by Genome Canada, Western Grains Research Foundation, Saskatchewan Pulse Growers, BASF, University of Saskatchewan, Global Institute for Food Security, Marche Polytechnic University (Italy), Palacky University Olomouc (Czech Republic), AGT Food and Ingredients.

Procedure:

If you are interested in completing this survey, please press on the link provided at the bottom of the page. By completing and submitting this questionnaire, your free and informed consent is implied and indicates that you understand the conditions of participation in this study.

Participation in this survey is voluntary, and you can decide not to participate at any time by closing your browser, or choose not to answer any questions you don't feel comfortable with. Survey responses will remain anonymous. Since the survey is anonymous, once it is submitted it cannot be removed.

This survey is hosted by Survey Monkey. Your data will be stored in facilities hosted in Canada. Please see the following for more information on Survey Monkey's privacy policy.
Completion of the survey should take approximately 15 minutes. Please feel free to email the researchers and ask any questions regarding the procedures and goals of the study.

Risks and Benefits:

There are no known or anticipated risks from participation in this study. Also, there are no direct benefits to you for participating in this research. However, the results of this research will help to improve specific qualities of the system in this current project, as well as to determine which features are desirable for future projects.

Confidentiality and Data Security:

All your responses are confidential and no identifiable information will be collected. Your responses will be safely stored on University of Saskatchewan OneDrive folders and password protected computers. Your responses will be kept for 5 years under the above security conditions. Your responses will be shredded or deleted 5 years after the completion of the study. After five years, all the data related to the study will be deleted with software that does not allow data recovery. There are no known risks to participating in this survey.

Contact Information and Research Ethics Clearance

If you have any questions about participation or you would like additional information to assist you in reaching a decision about participation, please do not hesitate to contact Professor Peter Phillips or Simona Lubieniechi.

This research project has been approved on ethical grounds by the University of Saskatchewan Behavioural Research Ethics Board. Any questions regarding your rights as a participant may be addressed to that committee through the Research Ethics Office ethics.office@usask.ca (306) 966-2975. Out of town participants may call toll free (888) 966-2975.

Sincerely,

Simona Lubieniechi, simona.lub@usask.ca

Peter W. B. Phillips, peter.phillips@usask.ca

14. References

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