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ORIGINAL ARTICLE

Adoption of herbicide resistance tests in German arable farming: Insights from the theory of planned behaviour

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Abstract

An increasing number of herbicide-resistant weeds challenge farming systems worldwide. Bans on active ingredients in chemical crop protection, which result in fewer weed control options, emphasise the importance of herbicide resistance management in arable farming. Resistance testing allows farmers to get an objective overview of the prevailing herbicide resistances on their land and to adjust their management strategies accordingly. Nevertheless, no study has examined farmers' adoption of herbicide resistance tests. For this purpose, an online survey with 197 German arable farmers was conducted. The adoption decision was investigated by applying the theory of planned behaviour framework. The results suggest that informing farmers of the economic benefits associated with herbicide resistance tests can facilitate widespread adoption. Furthermore, awareness of the availability of herbicide resistance tests needs to be raised through both advertising and crop consultants. Results from this study are relevant for several interest groups as the usage of herbicide resistance tests can help reduce the emergence of new resistance by optimising herbicide use at the farm level.

KEYWORDS

herbicide resistance management, herbicide resistance test, partial least squares structural equation modelling, theory of planned behaviour, weed management

JEL CLASSIFICATION

Q16, Q12

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1 | INTRODUCTION

Intensive farming practices in modern conventional agriculture systems are heavily dependent on the use of mineral fertiliser and chemically synthesised pesticides to protect and enhance yield (Pretty, 2018; Tilman et al., 2011). Oerke and Dehne (2004) stressed that the use of pesticides against weeds and other pathogens is important for safeguarding crop productivity and has brought massive increases in food production (Hicks et al., 2018). Nonetheless, incorrect use of pesticides (overuse, incorrect application and use of obsolete products) can lead to adverse effects on agricultural land, the surrounding flora and fauna, as well as human health. Associated hidden costs include pollution of groundwater and food, as well as costs for human health care (Bakker et al., 2021; Damalas, 2009; Despotović et al., 2019).

Weeds cause average yield losses of 35% worldwide (Hicks et al., 2018). Herbicides play a critical role in managing these losses by stabilising and increasing crop yields (e.g. Gianessi, 2013). Herbicide benefits are, however, contingent upon correct use, and incorrect application can lead to several adverse effects. One of the most noteworthy effects is the development of herbicide resistance. Herbicide resistance can be defined as the inherited ability of a weed population to survive a herbicide application that is normally lethal to a vast majority of individuals of that species (Powles et al., 1996). Addressing herbicide resistance is, therefore, crucial not only for maintaining agricultural productivity but also for reducing the broader ecological impacts of herbicide use.

Ulber and Rissel (2018) showed that farmers have relied mostly on experts and their own perception in detecting herbicide resistances. A more precise analysis could be achieved by using the results of a commercially available herbicide resistance test, which provides a cost-effective, objective and detailed overview of resistances against active ingredients.

With such tools, farmers can more easily adjust their weed control and tailor herbicide usage to the current situation. In consequence, farmers can reduce the quantities applied and their environmental footprint, which is line with the integrated pest management principles, and thereby contribute to the overall goal of sustainable agriculture. Furthermore, herbicide resistance tests can also help to ensure that the range of active ingredients is not further restricted. In addition to intrinsic reasons for farmers using herbicide resistance tests, a number of pesticide reduction policies (Candel et al., 2023; Jacquet et al., 2022) or bans on certain active substances (Finger et al., 2023) put even more pressure on farmers to adjust their weed and resistance management. Despite the many advantages, adopting herbicide resistance tests is not yet widespread among farmers. Even more surprising, no study has yet looked at farmers' attitudes and decision-making with respect to herbicide resistance tests.

With respect to voluntary adoption decisions, focussing on the behavioural perspective is particularly warranted if the goal is to motivate adoption (Dessart et al., 2019), as is the case for herbicide resistance tests. Hence, it is reasonable to focus exclusively on social-psychological factors to investigate the adoption of herbicide resistance tests. A well-known theoretical framework, which especially accounts for the influence of social-psychological factors in decision-making, is the theory of planned behaviour (TPB) (Ajzen, 1991). The compatibility of using the TPB framework to explain farmers' behaviour in this context has not been examined yet.

To fill this research gap, this study aims at understanding farmers' attitudes and behaviour towards the use of herbicide resistance tests by using the TPB framework. To the best of our knowledge, this is the first study that examines the influence of attitudinal variables on farmers' adoption process of herbicide resistance tests. Additionally, this study aims to offer insights into farmers' information sources about the use of crop protection products and farmers' perception on how well they feel informed about the topic of herbicide resistance. For this purpose, an online survey was conducted with 197 conventional arable farmers across Germany. The model for the TPB is estimated via partial least squares structural equation modelling

(PLS-SEM). The TPB successfully captures a large amount of latent information in farmers' decision-making. Results reveal that farmers' attitude towards adopting herbicide resistance tests is the strongest predictor with the intention to use such tests followed by the perceived behavioural control of performing these tests and subjective norm from peers and advisors. Understanding farmers' attitudes and behaviours towards the use of herbicide resistance tests can facilitate the adoption of these instruments in conventional arable farming and ultimately the adoption of herbicide resistance management strategies. In the long run, promoting herbicide resistance testing by using the results of this study can thus help to ensure food safety and farm profitability. Lastly, potential opportunities of merging and gathering the results from resistance tests from individual farmers could also strengthen data availability on herbicide resistances occurring in the farming sector as a whole. Hence, the results from this study are of interest for both researchers and farmers, as well as extension services and providers of herbicide resistance tests as they have both theoretical and practical implications.

The remainder of the paper is organised as follows: In Section 2, some background information is given, followed by the generation of the hypotheses for the TPB in Section 3. Materials and methods are presented in Section 4. Section 5 includes the results and discussion. The last section contains the concluding remarks.

2 | BACKGROUND

According to Ervin et al. (2019), weed sensitivity to herbicides is an underappreciated ecosystem service. By disrupting biochemical and/or physiological processes, herbicides kill weeds and thereby ensure yield and quality of the crop. The evolution of herbicide resistances is directly correlated with the frequency of historical herbicide use (Hicks et al., 2018). To be specific, an increased use of one active ingredient, when other weed control practices are absent, can rapidly give rise to herbicide resistances (Hurley & Frisvold, 2016; Peterson et al., 2018). Furthermore, the scarcity of new products and the ban on many active ingredients increase the likelihood of emerging herbicide resistances in the future (Peterson et al., 2018). The first herbicide resistances were already detected in the 1950s (Switzer, 1957). The total number of herbicide-resistant weed occurrences has steadily increased since the first reports in the 1950s. The reported numbers are high, especially in Europe, Australia and the United States. Regarding specific crops, the highest number of herbicide-resistant species is reported in wheat cultivation followed by maize and rice. This underlines the global problem of increasing herbicide resistance, with currently more than 500 herbicide-resistant species listed in the International Herbicide-Resistant Weed Database (Heap, 2022). The actual number is probably even higher as not all resistant species are likely to be officially listed (Harrington & Ghanizadeh, 2024; Peterson et al., 2018). The increased occurrence of herbicide resistances threatens food security and can cause further environmental and human health damages when herbicides are overused or when the farmer adds further active ingredients to the mixture (Pannell et al., 2016; Peterson et al., 2018).

The characteristics of herbicide resistance management, namely the immediate short-term costs and uncertain long-term benefits, make it rather unlikely that farmers rapidly adopt strategies to delay the emergence of resistances as they focus more on the immediate costs. Herbicide resistance management requires an integrated approach that goes beyond relying on chemical control and encompasses best management practices that reduce the selection pressure on weeds. These practices, while potentially adding to short-term management costs, contribute to the mitigation of herbicide resistance evolution, thereby preserving the efficacy of herbicides as a valuable agricultural resource over a long-term period (Norsworthy et al., 2012). Likewise, herbicide resistance testing, as part of herbicide resistance management, comes with costs such as the price itself and initial adjustments

in farming practices based on test outcomes. As a result of the focus on short-term costs, farmers seem to wait for resistance to occur and then make a comprehensive adjustment to their weed management (Pannell & Zilberman, 2001). Even if new active ingredients are approved, herbicide resistance can develop over a short period of time, rendering even new products ineffective if they are overused (Hicks et al., 2018). Consequently, an effective instrument is needed to persuade farmers to adopt effective herbicide resistance management strategies. For this purpose, herbicide resistance tests are suitable instruments as they provide objective knowledge about the emergence of herbicide resistances. In the long term, farmers will benefit by implementing precise resistance management measures (Livingston et al., 2016) based on the test results. Such benefits include, for instance, reduced risk of yield loss due to prolonged efficacy of herbicides and the potential for lower overall herbicide use. Currently, there are two commercial providers who conduct herbicide resistance tests for farmers in Germany. Research institutions in Australia, which offer such tests, include the Australian Herbicide Resistance Initiative (AHRI) and the Australian Grains Research & Development Corporation (GRDC). In the United States, the Auburn University Herbicide Resistance Diagnostic Lab offers herbicide resistance tests. Still, no study has yet empirically investigated farmers' adoption of herbicide resistance tests.

3 | HYPOTHESIS GENERATION

Farmers' adoption decisions are usually not based solely on objectively measurable benefits; otherwise, all farmers would decide to adopt a beneficial technology or practice (Diederer et al., 2003). It is, rather, the perception of the benefits, which plays a crucial role in the adoption process. It has been argued that ignoring the influence of social-psychological factors (e.g. attitudes and beliefs) in the adoption process could result in an incomplete understanding of farmers' behaviour (Ataei et al., 2021; Austin et al., 1998). In the case of herbicide resistance management practices, Hurley and Frisvold (2016) also stress that while economic factors provide important incentives, they are not the only motivators for farmers.

In the TPB, an individual's intention is assumed to be the predecessor of their behaviour. The intention originates from the constructs: *Attitude towards the Behaviour*; *Subjective Norm*; and *Perceived Behavioural Control* (Ajzen, 1991). The TPB has been previously used in the agricultural¹ context to explain, for instance, the adoption of mixed cropping (Bonke & Musshoff, 2020). In the context of pesticide application, the TPB has also been used to explain the adoption of integrated pest management practices (Despotović et al., 2019; Rezaei et al., 2019), the use of pesticides (Bagheri et al., 2019) and behaviour towards safe pesticide handling (Bagheri et al., 2021). In the following, the hypotheses of the proposed extended TPB model for the adoption of herbicide resistance tests are derived and the model is graphically depicted in Figure 1.

The construct *Attitude towards the Behaviour* in the TPB measures an individual's positive or negative evaluation about the behaviour in question (Ajzen, 1991). With respect to herbicide resistance tests, the construct refers to farmers' evaluation of the usefulness of and interest in the tests results, respectively. A more positive attitude towards the herbicide resistance test is generally assumed to increase farmers' *Intention* while a negative attitude decreases it as is displayed in the following hypothesis:

H1. *Attitude towards the Behaviour has a statistically significant influence on farmers' Intention to use herbicide resistance tests.*

¹A recent review on the use of the TPB in the agricultural context can be found in Sok et al. (2021).

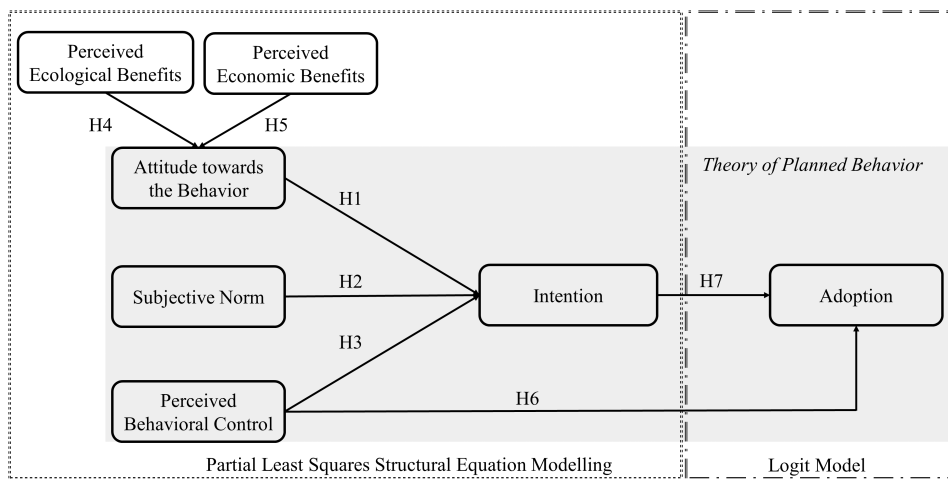


FIGURE 1 Proposed empirical model based on the theory of planned behaviour (Ajzen, 1991) for the adoption of herbicide resistance tests in German agriculture with the corresponding hypotheses (H) and applied estimation techniques.

Subjective Norm is the construct in TPB, which refers to an individual's perceived social pressure to behave in a certain manner. Specifically, *Subjective Norm* represents the influence of an individual's social environment (e.g. colleagues and extension services) on individuals' decision-making processes (Ajzen, 1991). Subjective norms can be differentiated into injunctive norms, that is what an individual perceives is expected of them by others, and descriptive norms, that is what others actually do themselves (Dessart et al., 2019). With regard to business decisions in general (Ohlmer et al., 1998) and pesticide applications specifically (Bakker et al., 2021; Pannell & Zilberman, 2001), professional colleagues' and advisors' opinions play a major role for farmers. Thus, descriptive norms in our context are defined by the perceived prevalence of behaviours among peers, such as the extent to which neighbouring farmers and crop consultants advocate for resistance tests. Accordingly, it can be assumed that professional colleagues' and advisors' opinions, as a descriptive *Subjective Norm*, also have an influence on the *Intention* to use herbicide resistance tests as shown in the following hypothesis:

H2. *Subjective Norm has a statistically significant influence on farmers' Intention to use herbicide resistance tests.*

Perceived Behavioural Control refers to the extent that an individual perceives performing the behaviour in question to be difficult or easy (Ajzen, 1991). Specifically, *Perceived Behavioural Control* can be attributed to an individuals' engagement in the behaviour in question based on their access and requirement of resources (e.g. money, time and skills) (Ajzen, 1985). In terms of herbicide resistance testing, this means access to herbicide test providers, the time commitment of collecting and sending in the seeds as well as correctly interpreting the resistance profile and transferring its implications to on-farm weed management. When the person perceives the behaviour execution as easy (difficult), the *Intention* to perform the behaviour increases (decreases). The following hypothesis is therefore derived:

H3. *Perceived Behavioural Control has a statistically significant influence on farmers' Intention to use herbicide resistance tests.*

Pannell and Zilberman (2001) emphasise that farmers may apply pesticides incorrectly causing a lack of efficiency and leading to overuse, which in turn can result in a greater negative

impact on the environment. Furthermore, farmers often respond to resistant weeds with herbicide mixtures containing additional active ingredients resulting in more negative environmental effects and also increasing the possibility of building new resistances (Pannell et al., 2016). However, farmers who are highly concerned about negative externalities associated with pesticides are more likely to take measures to reduce pesticide use (Bakker et al., 2021; Stallman & James Jr, 2015). Reliable results of herbicide resistance tests can serve as a motivator to use the optimal amount of the active ingredient or to adjust weed management efficiently, which can benefit the environment due to less overuse of herbicides. Hence, *Perceived Ecological Benefits* associated with using herbicide resistance tests can lead to a more positive (negative) attitude towards these tests and thus indirectly increase (decrease) the *Intention* to use them. The following hypothesis is therefore derived:

H4. *Perceived Ecological Benefits have a statistically significant influence on farmers' Attitude towards the Behaviour towards herbicide resistance tests.*

Weeds cause average yield losses of 35% worldwide (Hicks et al., 2018). The costs incurred directly by farmers due to weeds are composed of yield and quality losses (Alemseged et al., 2001; Norsworthy et al., 2012). The emergence of herbicide-resistant weeds can pose an even greater threat to the profitability of arable farms (LeBaron & Gressel, 1982). Loss of control through herbicide resistances can double the economic costs of weeds (Hicks et al., 2018). However, Livingston et al. (2016) noted that adjustments to weed management due to resistances may reduce profits in the first years but can increase profits in the long run. Hence, *Perceived Economic Benefits* of using herbicide resistance tests can be assumed to have an influence on farmers' attitude towards herbicide resistance tests. If farmers perceive that they can (not) use active substances more efficiently on the basis of resistance test results and that the profits (do not) exceed the costs in the long term, they will have a more positive (negative) attitude towards the tests.²

H5. *Perceived Economic Benefits have a statistically significant influence on farmers' Attitude towards the Behaviour towards herbicide resistance tests*

In the TPB framework, the construct *Perceived Behavioural Control* and *Intention* directly influence the actual behaviour in question. The lower the probability that the behaviour in question is actually performed, the lower the *Intention* of the individual is, regardless of whether the individual is able to do so (Ajzen, 1991). This can be assumed to also hold true for herbicide resistance tests usage. Furthermore, increased *Perceived Behavioural Control* also increases the likelihood of the actual performance of the behaviour in question (Ajzen, 1991). The following hypotheses reflect these considerations:

H6. *Farmers' Intention to use herbicide resistance tests has a statistically significant influence on farmers' Adoption of herbicide resistances tests.*

H7. *Perceived Behavioural Control has a statistically significant influence on farmers' Adoption of herbicide resistances tests.*

²While conventional TPB applications often integrate various belief dimensions into broad attitudinal measures within an expectancy-value framework, our decision to delineate 'Perceived Ecological Benefits' and 'Perceived Economic Benefits' as separate constructs is driven by the specific context of sustainable agricultural practices. In this realm, economic and ecological considerations frequently motivate behaviour distinctly, necessitating a differentiated approach to fully capture the nuances of how these factors influence attitudes towards behaviours such as herbicide resistance testing. This approach aligns with the TPB by maintaining the core premise that attitudes are influenced by specific beliefs about the outcomes of behaviours, yet it introduces a level of specificity that addresses the complexities of sustainable agricultural practices.

4 | MATERIALS AND METHODS

4.1 | Survey and data collection

An online survey addressed to German farmers was conducted in 2021. Farmers were invited to participate in the survey via agricultural newsletters and social media. The survey was divided into three parts. In the first part, farmers were asked to provide sociodemographic and farm-related information. In the third part, farmers were asked to indicate their approval of 19 randomised indicator statements on 5-point Likert scales (1—high disagreement; 5—high agreement). The statements are used to estimate the constructs in the model as proposed in Figure 3. Ajzen (2020a, 2020b) provided standardised statements, which provide a valuable foundation from which we departed due to the unique nature of the context at hand. The development of the statements was guided by the Target Action Context Time (TACT) scheme with one exception for the specific timeframe as shown below.

- *Target*: The suspected resistant weed species on the farm.
- *Action*: Performing an herbicide resistance test.
- *Context*: Within the management of arable farming when resistance is suspected.
- *Time*: A specific timeframe is not given due to the conditional nature of the action. Specifically, timing of these tests is conditional upon the suspicion of resistant weeds rather than occurring at regular intervals.

According to the principle of compatibility, technical statements need to be formulated strictly repeating the TACT scheme (Ajzen & Fishbein, 2005). Recognising the critiques highlighted in the literature, including potential confounding between concept definition and measurement as well as the risk of inflating common method variance (cf. Kaiser et al., 2007), we employed a more flexible approach. Furthermore, we adapted the standard application of the TACT to better align with the practical realities of farming behaviour without being restricted by overly rigid survey constructs that might obscure true behavioural associations. Thus, this flexibility enhances the validity of the survey by aligning it more closely with the actual decision-making environments of respondents. For instance, the context of arable farming was woven into the survey narrative and instructions rather than being repetitively stated in each statement. The rationale behind this is that arable farming provides a uniform backdrop for all survey participants. Explicitly repeating this context in every item could be redundant, as the environmental and operational context remains constant across the survey, and all participants are conscious of this.

Before the farmers evaluated the statements, they received an explanatory text about the herbicide resistance tests. This ensured that all farmers had the same basic knowledge of resistance testing in order to be able to evaluate the statements in a reliable way (translated from German):

In this survey, the term resistance testing means the development of a resistance profile. For this, mature seeds of a specific weed are collected at the end of June/ beginning of July and sent to the laboratory. There, a profile of the effectiveness of different herbicides on the specific weed is compiled and the existing resistance mechanisms of the weeds are reported. With the help of the profile, long-term herbicide planning can be established.

To address the research question in a meaningful way, purposive sampling or judgement sampling for conventional arable farmers who manage more than five hectares of arable land was applied (German Farmers' Association, 2021). Furthermore, we ensured that all farmers have winter cereal in their crop rotation as these dominate crop rotations

in Europe (Peterson et al., 2018) (see also Section 2). Objectively, these are the farmers who deal with weed management issues and possibly herbicide resistances. Finally, the sampling method ensured transferability of the results to other regions with comparable cropping systems.

4.2 | Partial least squares structural equation modelling and logit model

Figure 3 shows the model to be estimated with the corresponding estimation techniques. The left part of the model including farmers' intention to adopt a herbicide resistance test is estimated using PLS-SEM. For the binary adoption variable, a logit model is estimated. Both techniques are explained in the following: PLS-SEM is a nonparametric variance-based approach to SEM, which aims to maximise the endogenous construct explained variance (R^2) (Hair et al., 2022). A detailed explanation is given in Appendix S2.

The path model in PLS-SEM consists of two elements: the measurement model (outer model) and the structural model (inner model), which are evaluated in a two-step approach following Hair et al. (2022). A reflective measurement model measures the relationship between a construct and its indicators. The measurement model assessment includes indicator reliability (loadings, λ), internal consistency (composite reliability, CR), convergent validity (average variance extracted, AVE) and discriminant validity (Heterotrait–Monotrait ratios, [$HTMT$]) (Hair et al., 2022; Henseler et al., 2015). Indicator reliability is established if standardised loadings, λ , exceed the threshold of 0.7, which indicates that more than 50% of the indicators' variance is explained by the construct. Values for composite reliability $CR > 0.7$ and < 0.95 establish internal consistency, which means that all indicators to be tested measure the same construct. Convergent validity is established by estimating the average variance extracted, AVE , which should exceed the threshold of 0.5. An AVE value above 0.5 indicates that a construct explains more than half of the variance of its indicators. Values for the $HTMT$ correlations should not exceed 0.9 to establish discriminant validity. Discriminant validity ensures that all constructs are separable from each other and that indicators only represent one construct (Hair et al., 2022).

Before estimating the structural model, variance inflation factors (VIF) are estimated to check for multicollinearity. In the structural model, the relationship between exogenous and endogenous constructs is estimated and given as standardised path coefficients, β (direct effect). A bootstrapping procedure with 10,000 subsamples is applied to estimate t -statistics and confidence intervals (CI) of the standardised path coefficients (β) and also to estimate CI for the $HTMT$ values. The estimation of standardised path coefficients allows for a comparison of the relative magnitude associated with different paths. Estimation of the PLS-SEM was carried out using *SmartPLS 4* (Ringle et al., 2015).

The target endogenous variable in the model is a binary variable with the following specification: 1—adoption of herbicide resistance tests and 0—no adoption of herbicide resistance tests. Applying the estimation procedure of PLS-SEM to the binary variable in the model would result in biased standard errors (Hair et al., 2014). Hence, the construct scores of the constructs *Intention* and *Perceived Behavioural Control* are implemented as independent variables in a logit model on the adoption variable. Estimation for the logit model was carried out using *STATA 14.2*.

5 | RESULTS AND DISCUSSION

5.1 | Descriptive results

Table 1 shows the descriptive results for the sample of 197 farmers. With respect to sociodemographic and farm characteristics, the sample is slightly biased towards farmers who

are younger than the German average. There is a stronger bias in the sample with regard to gender, higher education and regional distribution across Germany. The sample contains a higher share of male farmers (96.4%) than the German average (90%). Furthermore, 46.2% of the farmers in the sample hold a university degree, which exceeds the German average of 12% by far (German Farmers' Association, 2021). The share of winter cereals in the average farmers' crop rotation amounts to 51.9%. As expected, due to our sampling method, 97% of the farms are solely managed conventionally.

In the sample, 16.8% of the farmers have already used a herbicide resistance test. Only 21.8% are sure that they do not have herbicide-resistant weeds on their farm, while 55.5% are sure that they have herbicide-resistant weeds. Of the farmers who are sure they have herbicide-resistant weeds or are unsure whether they have herbicide-resistant weeds, 84.6% have already adjusted their weed management.

The upper part of Figure 2 shows the response distributions of farmers sources of information about crop protection production. The selection of sources was based on Ulber and Rissel (2018). The vast majority of farmers in the sample (95.43%) rely on personal conversations with consultants, farm-related publications (81.22%) and official crop consulting service publications (69.54%) as information sources for the use of crop protection products. Fewer than 10% feel that they are informed enough about the topic of herbicide resistance by the named sources (lower part of Figure 2).³

5.2 | Estimation results

Tables 2 and 3 present the estimation results for the measurement model.⁴ Table 2 shows the mean and standard deviation for each indicator, as well as their loadings (λ) on the respective construct. The indicator loadings are, with five exceptions, above the common rule of thumb of 0.7 (Hair et al., 2011). Hair et al. (2022) recommend that indicators between 0.4 and 0.7 should remain in the model due to their impact on further model results and validity. Bootstrapping revealed that all indicator loadings are statistically significant ($p < 0.001$). Hence, all indicators remained in the model as proposed. All values for composite reliability (CR) and average variance extracted (AVE) exceed the recommended threshold of 0.7 and 0.5, respectively, establishing internal consistency and convergent validity in the model. Minimum and maximum VIFs for the outer model are 1.230 and 1.815, respectively. VIFs < 5 indicate that multicollinearity is not at a critical level (Hair et al., 2022).

Descriptive results from Table 2 for the evaluation of the statements reveal that respondents show a positive attitude towards herbicide resistance testing, with mean scores ranging from 4.21 to 4.32, indicating a general agreement on its advantages and importance in arable farming (*Attitude towards the Behaviour*). There is variability in farmers' perceptions of their capability, with mean scores from 2.66 to 3.89, suggesting challenges such as access to testing providers and time capacity for sample collection (*Perceived Behavioural Control*). Mean scores from 3.21 to 3.55 reflect a moderate agreement to the statements about the influence of others who advocate for the use of herbicide resistance testing (*Subjective Norm*). Farmers agree (mean scores from 3.63 to 3.98) that herbicide resistance testing can reduce negative environmental impacts and is important for sustainable management, indicating a recognition

³Further results on farmers' perception of the development of herbicides resistances can be found in Appendix S1.

⁴An anonymous reviewer suggested that *Perceived Economic Benefits* and *Perceived Ecological Benefits* should be employed as formative indicators of the construct *Attitude towards the Behaviour*. The indicators in *Perceived Economic Benefits* and *Perceived Ecological Benefits* are not merely collections of independent beliefs but are each indicative of broader underlying attitudes towards ecological and economic aspects of herbicide resistance testing, hence the choice of reflective indicators. Nevertheless, a new estimation with formative indicators can be found in the Appendix S3.

TABLE 1 Descriptive statistics (*N* = 197).

Variable	Description	Mean	SD	Min	Max	Ger. Avg. ^a
Sociodemographic and farm characteristics						
Age	Farmers' age in years	44.868	12.939	22	71	—
	<25 years	0.061	—	0	1	0.08
	>25 and ≤35 years	0.259	—	0	1	0.15
	>35 and ≤45 years	0.157	—	0	1	0.14
	>45 and ≤55 years	0.279	—	0	1	0.24
	>55 years	0.244	—	0	1	0.36
ArableLand	Hectares of arable land managed by the farmer	337.847	593.323	5	4300	—
	>5 and ≤10 hectares	0.010				0.02
	>10 and ≤20 hectares	0.046				0.05
	>20 and ≤50 hectares	0.122				0.12
	>50 and ≤100 hectares	0.228				0.19
	>100 and ≤200 hectares	0.238				0.21
	>200 and ≤500 hectares	0.223				0.16
	>500 hectares	0.137				0.25
Gender	1, if the farmer is male; 0 otherwise	0.964	—	0	1	0.89
HigherEduc	1, if the farmer has a university degree (at least B. Sc); 0 otherwise	0.462	—	0	1	0.14
Risk	Farmers' general risk attitude (0—not at all willing to take risks; 5—risk neutral; 10—very willing to take risks) ^b	5.497	1.791	1	9	—
Region	Farm location in Germany					
	North—Schleswig-Holstein, Lower Saxony or Mecklenburg Western Pomerania	0.518	—	0	1	0.20
	East—Brandenburg, Saxony, Saxony-Anhalt or Thuringia	0.051	—	0	1	0.07
	West—North Rhine-Westphalia, Hesse, Rhineland Palatinate or Saarland	0.269	—	0	1	0.24
	South—Baden-Württemberg or Bavaria	0.162	—	0	1	0.48
ShareWinter	Share of winter cereals in the crop rotation	0.519	0.149	0.10	0.85	—
TypeFarm	1, if the farm is managed conventionally; 0, if the farm has organic branches beside the main conventional segment	0.970	—	0	1	0.88
Digital instruments in arable farming/plant protection						
DigiDocu	1, if the farmer uses a digital documentation instrument for crop management measures; 0 otherwise	0.741	—	0	1	—

TABLE 1 (Continued)

Variable	Description	Mean	SD	Min	Max	Ger. Avg. ^a
SmartPlant	1, if the farmer uses a smartphone and/or apps for plant protections purposes; 0 otherwise	0.650	–	0	1	–
Herbicide resistance information						
HerbResTest	1, if the farmer has used an herbicide resistance test; 0 otherwise	0.168	–	0	1	–
HerbResis	Do you have herbicide-resistant weeds on your farm?					
	Yes	0.564	–	0	1	–
	No	0.218	–	0	1	–
	I am not sure	0.218	–	0	1	–

Abbreviation: SD, standard deviation.

^aGerman Farmers' Association (2021).

^b11-point scale based on Dohmen et al. (2011).

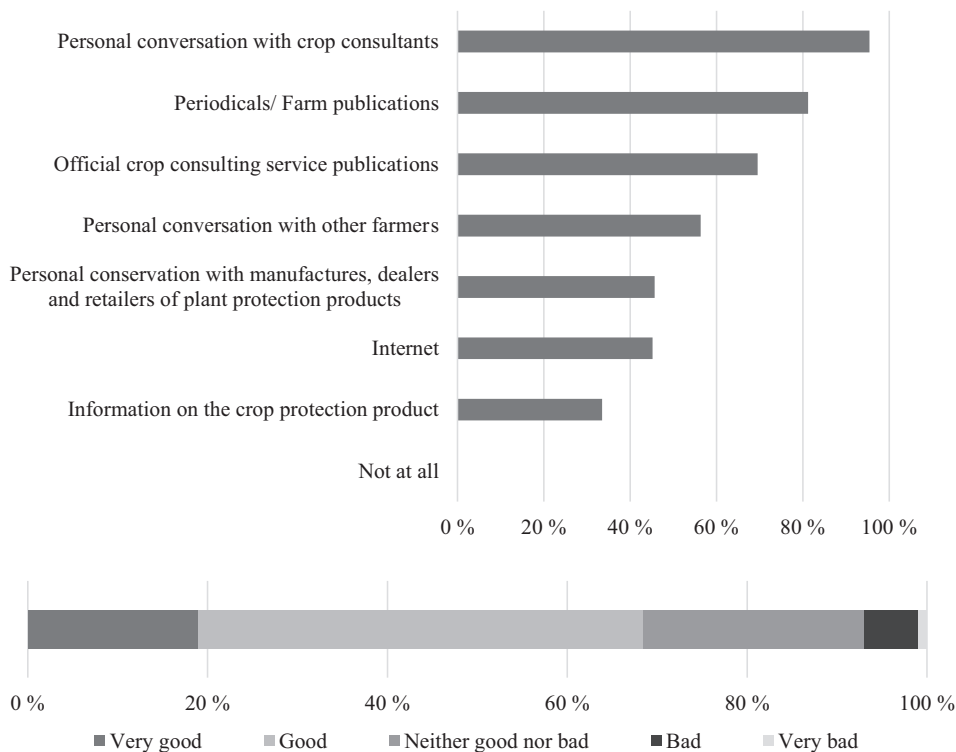


FIGURE 2 Response distribution of the answers regarding information sources about the use of crop protection products (multiple answers possible) and farmers' perception of how well they feel informed about the topic of herbicide resistance (no multiple answers possible). (N=197).

of its ecological advantages (*Perceived Ecological Benefits*). Economic aspects are also seen positively, with mean scores from 3.83 to 4.36, highlighting the perceived efficiency and cost-effectiveness of herbicide resistance testing in managing weeds and using crop protection

TABLE 2 Descriptive and measurement model results ($N=197$).

Construct			
Indicator statement ^a	Mean	SD	Loading λ (CI ₉₅) ^c
<i>Attitude towards the Behaviour</i> (CR=0.864, AVE=0.680) ^b			
I think there are many advantages to using herbicide resistance testing	4.21	0.86	0.849 (0.786; 0.894)
I think that the use of herbicide resistance testing in arable farming will become more important in the future	4.26	0.85	0.831 (0.753; 0.887)
A test to detect resistance to different herbicides (resistance profile) interests me	4.32	0.86	0.794 (0.683; 0.871)
<i>Perceived Behavioural Control</i> (CR=0.755, AVE=0.512) ^b			
I have the knowledge necessary to transfer herbicide resistance test results into my weed management	3.89	1.01	0.606 (0.373; 0.754)
I have the time capacity to collect and ship sufficient plant or seed samples	3.09	1.17	0.659 (0.420; 0.805)
I have access to herbicide resistance testing providers	2.66	1.55	0.857 (0.738; 0.943)
<i>Subjective Norm</i> (CR=0.797, AVE=0.567) ^b			
Neighbouring farmers believe that herbicide spraying adjusted by herbicide resistance testing results is advantageous over conventional herbicide spraying with general application rates	3.21	1.08	0.792 (0.684; 0.861)
My crop consultant advocates the use of herbicide resistance testing	3.55	1.15	0.696 (0.535; 0.812)
My professional colleagues believe that herbicide resistance testing is an important part of modern agricultural production	3.24	0.97	0.768 (0.599; 0.858)
<i>Perceived Ecological Benefits</i> (CR=0.821, AVE=0.535) ^b			
Negative environmental impacts caused by inappropriate herbicide use can be reduced through the use of herbicide resistance testing	3.94	0.90	0.752 (0.644; 0.825)
Pollution of water and soil from the use of pesticides can be reduced when herbicide resistance tests are used	3.63	1.15	0.683 (0.533; 0.780)
Herbicide resistance testing allows me to adjust my crop rotation so that resistance can be counteracted	3.91	0.90	0.726 (0.631; 0.801)
The use of herbicide resistance testing is important for sustainable management in arable farming	3.98	0.91	0.762 (0.607; 0.859)
<i>Perceived Economic Benefits</i> (CR=0.884, AVE=0.655) ^b			
Herbicide resistance tests allow me to use crop protection products more precisely	4.25	0.85	0.816 (0.724; 0.880)
Herbicide resistance testing allows me to manage my weeds more effectively	4.14	0.86	0.862 (0.811; 0.908)
Herbicide resistance testing allows me to use active ingredients more efficiently	4.36	0.85	0.776 (0.635; 0.868)
I think that the economic benefit of herbicide resistance testing is greater than the cost in the long run	3.83	0.92	0.781 (0.695; 0.842)

TABLE 2 (Continued)

Construct			
Indicator statement ^a	Mean	SD	Loading λ (CI ₉₅) ^c
<i>Intention</i> (CR = 0.907, AVE = 0.830) ^b			
I intend to incorporate herbicide resistance testing into my weed management	3.32	1.14	0.919 (0.895; 0.939)
I will not use herbicide resistance tests in the near future ^d	3.74	1.09	0.903 (0.850; 0.936)

Abbreviations: AVE, average variance extracted; CR, composite reliability; SD, standard deviation.

^aStatements were evaluated using a 5-point Likert scale (1—high disagreement; 5—high agreement).

^bCut-off level: CR >0.7 and <0.95; AVE >0.5.

^cIndicator loadings >0.7.

^dNumerical coding was reversed due to negatively formulated statements.

products (*Perceived Economic Benefits*). The statements about the intention to adopt herbicide resistance testing show moderate agreement (mean scores 3.32 and 3.74), suggesting a positive inclination towards its use in weed management practices (*Intention*).

Results for the *HTMT* criterion are given in Table 3. Discriminant validity is supported since none of the *HTMT* ratios exceeds the threshold of 0.9 (Hair et al., 2022; Henseler et al., 2015). In this case, we used the less conservative threshold of 0.9 for the *HTMT* ratio, since we included three conceptually related constructs in the model (*Attitude towards the Behaviour*, *Perceived Economic Benefits* and *Perceived Ecological Benefits*). However, to not only rely on the threshold, we also estimated the 95% confidence intervals (CI₉₅) of the *HTMT* ratios. A lack of discriminant validity can be excluded if a value of 1 does not fall in the CI₉₅ (Henseler et al., 2015). The results underscore that the constructs, especially *Attitude towards the Behaviour*, *Perceived Economic Benefits* and *Perceived Ecological Benefits*, maintain their distinctiveness, supporting their operationalisation as separate but related constructs influencing the adoption of herbicide resistance testing.

Table 4 shows the model results. Explained variance (R^2) of the constructs *Attitude towards the Behaviour* and *Intention* in the structural model amounts to 0.556 and 0.479, respectively. The results indicate that 48% of the variation in the farmers' intention can be explained by the proposed extended TPB model. Farmers' attitude has a statistically significant influence on the intention to use herbicide resistance tests ($\beta=0.484$), so the first hypothesis (H1) cannot be rejected. Hence, higher levels of a positive attitude towards herbicide resistance tests lead to a higher intention to use this instrument. Results also show that *Perceived Behavioural Control* has a statistically significant positive relationship with the *Intention* to use herbicide resistance tests ($\beta=0.215$). Thus, the model fails to reject the second hypothesis (H2). If a farmer perceives difficulties performing herbicide resistance tests, the intention to perform a test decreases. The results also cannot reject the third hypothesis (H3), which proposes a statistically significant effect of *Subjective Norm* on farmers' *Intention* to use herbicide resistance tests ($\beta=0.205$). Perceived pressure from other farmers and crop consultants reinforces farmers' intention to use such tests.

Perceived Ecological Benefits statistically significantly influence farmers' attitude towards herbicide resistance tests (H4) in a positive direction ($\beta=0.293$). Similarly, the path coefficient of *Perceived Economic Benefits* (H5) is statistically significant for the *Attitude towards the Behaviour* in a positive direct effect ($\beta=0.517$). The path coefficient from *Perceived Economic Benefits* to *Attitude towards the Behaviour* ($\beta=0.517$) is notably higher than that from *Perceived Ecological Benefits* ($\beta=0.293$), indicating a stronger influence of economic considerations on farmers' attitude and, indirectly, on their intention to use such tests.

TABLE 3 Heterotrait–Monotrait ratios (N=197).

	<i>Perceived Ecological Benefits</i>	<i>Perceived Economic Benefits</i>	<i>Attitude towards the Behaviour</i>	<i>Intention</i>	<i>Perceived Behavioural Control</i>
<i>Perceived Economic Benefits</i>	0.869 (0.758; 0.964)				
<i>Attitude towards the Behaviour</i>	0.857 (0.725; 0.958)	0.892 (0.769; 0.989)			
<i>Intention</i>	0.531 (0.342; 0.695)	0.674 (0.538; 0.784)	0.789 (0.669; 0.896)		
<i>Perceived Behavioural Control</i>	0.237 (0.165; 0.487)	0.395 (0.232; 0.645)	0.292 (0.128; 0.555)	0.519 (0.334; 0.713)	
<i>Subjective Norm</i>	0.600 (0.420; 0.784)	0.706 (0.534; 0.862)	0.609 (0.420; 0.782)	0.670 (0.581; 0.814)	0.506 (0.355; 0.743)

Note: Cut-off level: HTMT <0.9.
Abbreviation: CI₉₅, lower and upper bound of the 95% percentile bootstrap confidence interval (10,000 subsamples).

TABLE 4 Structural model and logistic regression results (N=197).

Partial least squares structural equation modelling ^a			
	Path	β (CI ₉₅)	t-statistics ^b
H1	<i>Attitude towards the Behaviour</i> → <i>Intention</i>	0.484 (0.354; 0.591)	8.040
H2	<i>Perceived Behavioural Control</i> → <i>Intention</i>	0.215 (0.118; 0.323)	4.113
H3	<i>Subjective Norm</i> → <i>Intention</i>	0.205 (0.092; 0.324)	3.454
H4	<i>Perceived Ecological Benefits</i> → <i>Attitude towards the Behaviour</i>	0.293 (0.151; 0.434)	4.064
H5	<i>Perceived Economic Benefits</i> → <i>Attitude towards the Behaviour</i>	0.517 (0.361; 0.662)	6.733

Logistic regression ^c			
	Path	Odds ratio (CI ₉₅)	z-statistics
H6	<i>Perceived Behavioural Control</i> → <i>Adoption</i>	5.117 (2.676; 9.785)	4.94
H7	<i>Intention</i> → <i>Adoption</i>	4.283 (2.007; 10.014)	3.66

^aAttitude towards the Behaviour (R²=0.556), Intention (R²=0.479).
^bBootstrapping results with 10,000 subsamples applied.
^cLog likelihood=−48.864, LR chi² (2)=80.33, *p*<0.001; McFadden Pseudo R²=0.451; McKelvey & Zavoina Pseudo R²=0.674; Nagelkerke Pseudo R²=0.563; Link test: n.s.; Hosmer–Lemeshow chi² (8)=1.66, n.s.; Pearson's chi² (161)=102.50, n.s.; Correctly classified=90.86%.

To investigate possible indirect effects, we test for the statistically significant indirect effects of *Perceived Ecological* and *Economic Benefits* via the *Attitude towards the Behaviour* towards the *Intention* to use herbicide resistance tests. The indirect effects can be seen as a sequence of the two direct effects, respectively. Hence, the statistically significant indirect effect of *Perceived Ecological Benefit* via the *Attitude towards the Behaviour* on the *Intention* is the product of the successive path coefficients (0.142=0.293×0.484). In the same manner, the statistically significant indirect effect of *Perceived Economic Benefits* via the *Attitude towards the Behaviour* on the *Intention* (0.250=0.517×0.484) is estimated. Higher levels of

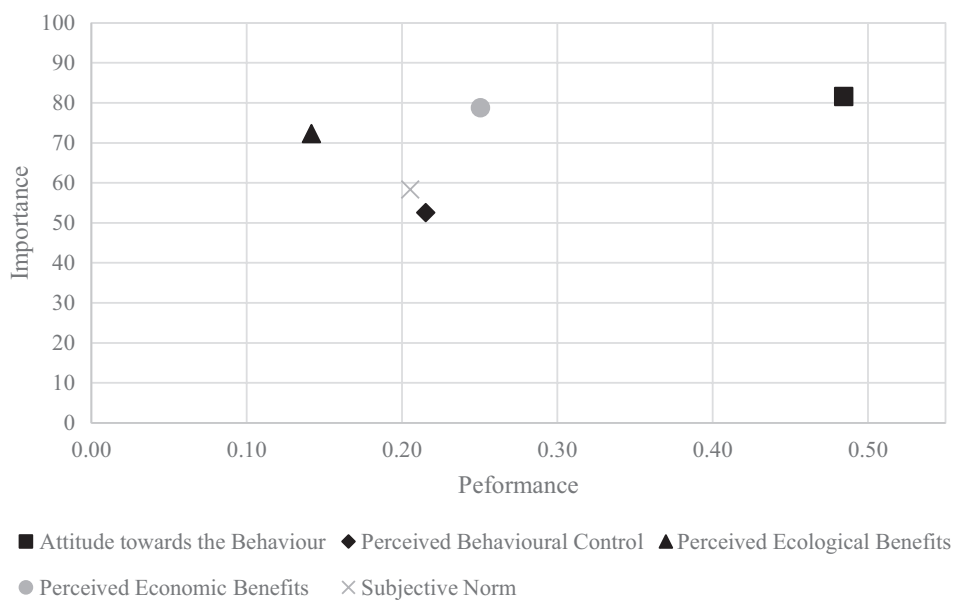


FIGURE 3 Importance–Performance Map for the target construct *Intention*.

Perceived Ecological and *Economic Benefits* lead to a positive increase in the *Attitude towards the Behaviour*, which in turn leads to a higher *Intention* to use herbicide resistance tests.

Figure 3 shows an Importance–Performance Map (IPMA) based on the estimated structural model up to the *Intention*. The index values of the inner models' constructs are rescaled so that they can take values between 0 and 100. The mean values indicate the specific constructs performance (0—lowest performance, 100—highest performance). It provides a measure of how well the sample of farmers scores on these constructs. Whereas the total effects express the importance of that particular construct in predicting the target construct *Intention*.

Results are interpreted as follows: A one-unit increase in the index value of the construct increases the index value of the endogenous target construct by the size of the total effect. IPMA results allow us to identify areas of improvement, which can be addressed by management and marketing activities. In order to increase the endogenous constructs performance, one should focus on constructs with relatively high importance (i.e. high total effect; *x*-axis) and a relatively low performance (*y*-axis) (Ringle & Sarstedt, 2016). Through the TPB framework, IPMA underscores the constructs that influence farmers' intentions while indicating areas of high performance (where farmers score well) and highlighting potential areas for improvement (where importance is high but performance is low).

In applying the IPMA within the TPB framework, our study further explicates the actionable insights that management and marketing activities can leverage to enhance farmers' intentions to use herbicide resistance tests. For example, while *Attitude towards the Behaviour* and *Perceived Economic Benefits* show high performance levels, indicating that farmers already recognise their value, *Subjective Norm* and *Perceived Behavioural Control* display both substantial effects on *Intention* and ample room for improvement. This suggests that strategies aimed at reinforcing the social approval from influential peers and at bolstering farmers' confidence in their ability to implement herbicide resistance testing could be particularly effective.

Lastly, the relationship between farmers' actual adoption decision and the constructs *Intention* and *Perceived Behavioural Control* (H6 and H7) is investigated via a logistic regression. The goodness-of-fit characteristics for the logit model are reported in Table 4. Results of the logistic regression show that the actual adoption of herbicide resistance test is statistically significantly influenced by farmers' *Intention* (Odds ratio [OR]=4.283) and the *Perceived Behavioural Control* (OR=5.177). Hence, H6 and H7 cannot be rejected.

5.3 | Practical implications

The results from the structural model conclude that the *Attitude towards the Behaviour* is the most relevant predictor of farmers' intention to use herbicide resistance tests (Table 4, Figure 3). This is in accordance with the literature as Ajzen and Cote (2008) stated that attitude is the best predictor of the intention and therefore essential for changing target behaviour. Similarly, Espig et al. (2022) identify farmers' attitude as a crucial driver of herbicide decision-making and that beliefs about new herbicides preventing herbicide resistance can lead to a lower motivation to review current practices. However, Bakker et al. (2021) found that descriptive norms—individuals' perceptions of the behaviours of others—is the primary driving force of farmers' intention to reduce pesticides. While our results underscore the important role of attitude, we acknowledge the potential for descriptive norms to exert considerable influence, particularly in tight-knit farming communities where the practices of peers can have a profound impact on an individual's behaviour.

The results for the construct *Perceived Economic Benefits* in the Importance–Performance Map (IPMA) (Figure 3) are also relevant. First, the effect of *Perceived Economic Benefits* is fully mediated through farmers' *Attitude towards the Behaviour* towards the *Intention*. Second, *Attitude towards the Behaviour* and *Perceived Economic Benefits* have the strongest influence on farmers' intention to use herbicide resistance tests. The observation is of great importance for the following reasons: With respect to the cost of herbicide resistances and herbicide resistance management, according to Norsworthy et al. (2012), it is scientifically clear that herbicide resistance management comes with short-term costs for farmers but includes long-term economic benefits, which result from avoiding additional future costs due to resistances and their consequences on arable land management. However, farmers are most likely to focus on immediate economic costs (Norsworthy et al., 2012), as they have to adjust their weed management or arable land management altogether. In contrast, benefits of an effective herbicide resistance management emerge at a later point in time, which encourages farmers to delay the adoption of herbicide resistance management strategies (Hurley & Frisvold, 2016). Indeed, farmers tend to have high discount rates, as they give relatively low weightings to long-term benefits but relatively high weightings to short-term costs (Pannell & Zilberman, 2001). Furthermore, it is also straightforward for a farmer to calculate the costs of adding an additional active ingredient to the mixture, but calculating the long-term costs of resistances and benefits of herbicide resistance management come with great uncertainty (Hurley & Frisvold, 2016). Hence, the goal should be to persuade farmers to adopt herbicide resistance tests and possible subsequent measures by informing them that the costs of antiresistance strategies are small compared with long-term costs of resistances (Orson, 1999). Herbicide resistance testing can serve as a cost-effective, robust and objective basis for convincing farmers to implement herbicide resistance management strategies. In this context, the long-term economic benefits of management adaptations need to be communicated. Following the above strategy, one can maintain or increase the *Attitude towards the Behaviour* level and thus also increase farmers' intention to use herbicide resistance tests. The prospects of success of this strategy are also supported in the results from Table 2, with regard to farmers' approval of the following statement, 'I think that the economic benefit of herbicide resistance testing is greater than the cost in the long run'.

Model results suggest *Perceived Behavioural Control* serves as a predictor for farmers' intention to use herbicide resistance tests (Table 4). Furthermore, the fact that the construct performed the lowest in the IPMA suggests major potential for improvement. Logically, increasing farmers' *Perceived Behavioural Control* also increases their motivation and self-confidence in adapting new practices or technologies. Effective marketing campaigns and instructive efforts by crop consultants that educate farmers about the properties of a new practice or technology, for example herbicide resistance tests, can reduce their uncertainty and can trigger an increase in the intention to use such instruments. In this context, it is particularly important to ensure that farmers are aware of the availability of herbicide resistance testing, as descriptive results in Table 2 show that farmers perceive a lack of access to providers. In our study region in Germany, even though two commercial providers are available, the results suggest that the farmers are not aware of their existence.

Subjective Norm also serves as a predictor of *Intention* (Table 4). Furthermore, the results of the IPMA map (Figure 3) suggest the constructs offer potential for performance improvement. This result is supported by the literature as the most important referents for farmers are neighbouring farmers or experts (e.g. Perry & Davenport, 2020). The positive relationship between *Subjective Norm* and farmers' intention to use herbicide resistance tests suggests that both other farmers and crop consultants can play vital roles. Other farmers can function as a channel to disseminate information about herbicide resistance tests and also persuade other farmers to adopt these instruments. This is also supported by the descriptive statistics of the indicator ratings (Table 2). Specifically, to leverage this construct, awareness campaigns could showcase endorsements such as successful farmers who advocate for herbicide resistance testing. The results stress the importance of networks influencing farmers' decision-making. In this vein, focussing on professional meetings of farmers where growers have the opportunity to interact directly with each other can be used to communicate the associated benefits in herbicide resistance testing. Furthermore, having neighbouring farmers at these meetings also has the advantage of counteracting farmers' feelings that they cannot make any difference (Shaw, 2016). In addition, emphasising the identified drivers of attitude through recommendations from crop consultants could also increase farmers' intention to use herbicide resistance tests. In particular, crop consultants should increase the awareness of the use of herbicide resistance tests, since, according to Figure 2, consultants are an important source of information on the use of crop protection products for most farmers.

Herbicide resistance in weeds is a topic that is intensively discussed in the scientific literature (Busi et al., 2021; Peterson et al., 2018), and most farmers report that the weed problem remains unchanged or is worsening (Alemseged et al., 2001). In spite of the persistent problem, a majority of the farmers expect substitute herbicides to be allowed on the market in the near future. This expectation is also observed in the literature (Bagavathiannan & Davis, 2018; Norsworthy et al., 2012). Crucially, it has been noted that farmers who are confident that new herbicides will be released are less likely to adopt herbicide resistance management practices (Llewellyn et al., 2002). Marketing plans and extension services should not solely focus on promoting herbicide resistance tests and associated benefits. In addition, they should also disseminate information about the market approval situation of new herbicides or active substances⁵ and general information about resistances as well as herbicide resistance management.

In summary, the analysis reveals that an integrated approach, which combines the influential aspects of attitude, subjective norms and perceived behavioural control, is critical for designing effective interventions. By leveraging the unique effects of each explanatory construct,

⁵No new modes of action have been developed for over 30 years (Shaw, 2016).

communication and awareness strategies can be tailored to comprehensively address the factors that contribute to the adoption of herbicide resistance tests.

5.4 | Research outlook

While our purposive sampling method was instrumental in generating targeted insights into the adoption of herbicide resistance testing, we recognise that it introduces a selection bias that may affect the transferability of our findings. Furthermore, the demographic profile of our respondents is notably characterised by a high share of university-educated individuals. It is possible that university-educated farmers have a greater interest in research topics such as herbicide resistance testing. Therefore, the findings should be interpreted with caution, considering the sample's potential bias towards more educated individuals. In addition, future studies should seek to validate our results in other country settings and with more representative samples for which this study provides the necessary framework. This holds especially true for the United States and Australia, which have a resistance problem that is comparable or more pronounced than in Germany, although with different authorised herbicides (Pannell et al., 2016).

As the study from Bakker et al. (2021) also highlights the role of the descriptive norm, adding injunctive norms could be of interest for future research. Furthermore, it could be interesting to investigate in depth if results from herbicide resistance tests lead to actual on-farm adjustments. Lastly, it is of great importance to also assess farmers' willingness to pay for herbicide resistance tests since Ulber and Rissel (2018) showed that herbicide resistance management strategies are not used by farmers due to cost.

6 | CONCLUDING REMARKS

The ongoing emergence of new herbicide resistances negatively impacts farming systems and the environment globally. Herbicide resistance tests, which are now commercially available, can help facilitate on-farm resistance management and thus contribute to reducing the emergence of new herbicide resistances. The present study explores the influence of constructs on farmers' adoption behaviour regarding the use of herbicide resistance tests. To this end, a model for an extended TPB was estimated using PLS-SEM and a binary logit model based on a sample of 197 German conventional arable farmers. This study provides first and novel evidence of farmers' behaviour regarding the use of herbicide resistance tests, which could be fruitful for both researchers and farmers as well as extension services and providers of herbicide resistance tests. Furthermore, this study provides insights into the farmers' perception of changing weed densities and the on-farm occurrence of herbicide-resistant weed species.

It was farmers' attitude that contributed the most in explaining the intention to use tests. Additionally, results show that sensitising farmers to associated economic and ecological benefits promotes a positive attitude towards herbicide resistance testing, which can ultimately lead to higher test usage rates. Furthermore, farmers' awareness of the potential supply of herbicide resistance testing needs to be increased by advertising and through recommendations from consultants. It is important to communicate the potential economic benefits of using these instruments in the awareness raising campaigns. Likewise, there should be promotional activities at meetings and conferences for farmers and also efforts to ensure that crop consultants make their farmers aware of the possibility of using resistance testing. Lastly, more information about herbicide resistances, herbicide resistance management and options for adapting weed management should be provided by extension services.

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DATA AVAILABILITY STATEMENT

All data associated with this paper can be made available upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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