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Can gene-editing accelerate the protein shift? Consumer acceptance of an upcycled meat-substitute

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ABSTRACT

Transforming waste in the production stage to food (upcycling) can contribute to increased environmental sustainability in the food systems. The side-stream in potato starch production contains protein, and gene-editing enables upcycling of potato-protein while avoiding the use of chemical processes in the extraction of food grade protein. We explore the demand for products containing this upcycled protein. Data were collected via an online survey of 1508 Swedish consumers who completed a choice experiment in which they selected among different sausages made from meat, soy, peas or potato-protein. Although meat is the most preferred product type, respondents choose potato-protein over soy and pea-protein. Upcycled potato-protein products are predicted to draw on the market share for meat more than from soy and pea-protein, suggesting considerable potential environmental benefits. The acceptance of upcycled products is not significantly different depending on if the upcycling is achieved by a chemical process or gene-editing (CRISPR-Cas9) techniques. We discuss the importance of the legal status of gene-editing and the role this may play in reducing food waste. Further, we discuss how policy makers can play an important role in reducing food waste, by means of regulations and by encouraging public and private initiatives that accommodate upcycling in the different stages of food production.

1. Introduction

Reducing food waste and shifting consumption patterns towards more plant-based diets are important changes to ensure sustainable consumption and production patterns (Mbow et al., 2019). About 8–10 % of the global greenhouse gas emissions come from food that is wasted at some stage (Mbow et al., 2019), and initiatives and policies that can tackle food loss are called for (FAO, 2017). When food loss in the production stage is transformed to food, this is referred to as 'waste-to-value' or 'upcycled' food products, and this is an area that has been identified to hold great potential for reducing food loss (Aschemann-Witzel and Stangherlin, 2021). Further, the transition towards more environmentally sustainable food systems entail increased consumption of plant-based proteins in favour of meat (Crippa et al., 2021; Godfray et al., 2018; Willet et al., 2019), since meat production causes higher levels of greenhouse gas emissions and requires larger land areas relative to other protein sources (Poore and Nemecek, 2018). Plant-based meat-analogue products provide a feasible transition towards increased plant-based diets and reduced meat consumption, and the market for such products has expanded in recent years and is expected to grow further (Statista, 2024). Reducing food loss by producing upcycled food prepared from plant-based protein that is currently wasted or directed to non-food side-streams in the production and processing stages for agricultural crops represent a resource efficient option to reduce the environmental impact (Bartek et al., 2022).

Europe is the largest market for plant-based meat-substitutes (EUVEPRO, 2019), and these are predominately made using soy (Allied Market Research, 2021). An important reason for the dominance of soy protein is its nutritional and functional qualities combined with low-cost and high-availability. However, the EU relies heavily on importing soy from South America, and the production of soy in South American countries is associated with negative environmental consequences related to aspects such as soil erosion, global transportation (Davis et al., 2010; Eriksson et al., 2018) and loss of biodiversity (Guilpart et al., 2022). Therefore, replacing soy imports with EU-produced vegetable protein crops could have environmental benefits (Davis et al., 2010; Guilpart et al., 2022). Use of protein from peas, beans, lentils and so on represent alternative plant protein sources for EU food processors, although issues around protein functionality as well as the quantities available provide challenges to such adoption (Agrosynergie, 2018).

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Potato-protein represents a large-scale opportunity to substitute animal proteins and/or imports of soy crops. The potato-protein end up in a side-stream in the starch production (Bartek et al., 2022), and although the protein is of high nutritional quality, it is currently mainly used for animal feed, fertilizer or thrown away directly (Fu et al., 2020). While possible to generate food grade protein from the potato starch by-product, it requires high use of energy and use in chemical protein-cleansing processes allowing the toxic substances to be removed (Hussain et al., 2021). New breeding technologies (NBT), including the genome-editing technique CRISPR-Cas9, allow increasingly precise plant breeding (Turnbull et al., 2021). This presents an alternative method for removing the toxic compound in potato-protein compared to the currently available energy intensive and therefore costly chemical protein-cleansing processes (Bartek et al., 2022; Zheng et al., 2021).

On this background, the first objective of this study is to examine consumer preferences and demand for plant-based meat substitutes from side-streams, i.e. from produce that is currently not used as food. Consumer perception and acceptance of such upcycled food ingredients is an emerging field of research, where the main outcomes of investigation are stated acceptance, liking, attitudes and willingness to eat or buy (Grasso et al., 2023; Lu et al., 2024; McCarthy et al., 2020). However, there are only few studies that take an economic approach and investigate the willingness to pay and make market predictions (Asioli and Grasso, 2021; Bhatt et al., 2020; Kawata and Kubota, 2018).

The second objective is to investigate if demand for upcycled plant-based protein varies due to the technology used in the upcycling process. Specifically, we compare consumer preferences for the currently available chemical protein-cleansing process with the adoption of genome-editing. Although NBT can contribute to increased resource efficiency of existing produce and thus serve the transition towards more sustainable food systems, the adoption depends on consumer acceptance and demand for products developed by such technologies. Overall, there is evidence of consumers preferring traditional breeding technologies to NBT, although acceptance for NBT increases when it enables environmental benefits (Delwaide et al., 2015; Edenbrandt et al., 2017; Muringai et al., 2020; Paudel et al., 2023). Importantly, there is to the best of our knowledge no study that has investigate the acceptance of food made from upcycled ingredients that are developed by gene-editing.

The third objective is to explore which consumers that are likely to accept plant-based meat substitutes based on upcycled protein. The consumption of upcycled potato protein, and the adoption of gene-editing to more resource efficiently use the potato protein, may contribute to sustainability by reducing food loss and by replacing consumption of other less sustainable protein sources (Bartek et al., 2022). However, the magnitude of the environmental benefits from consuming upcycled potato-protein depends on which product is substituted, where environmental improvements are achieved for replacing meat, egg and imported Brazilian soymeal (Bartek et al., 2022). We contribute with insights on the expected substitution patterns that result from the introduction of upcycled potato-protein products and identify how acceptance of such products relates to consumer's current dietary patterns with respect to protein products.

This study contributes with insights that are of immediate policy relevance; first, we investigate consumer acceptance and the expected market reception for upcycled plant-based products, and thus contribute with economic insights that are missing in the available literature. Understanding consumer acceptance and the predicted market reception for upcycled ingredients is important from a policy perspective. The reduction of food waste is prioritized in the European Farm to Fork strategy (European Commission, 2023a), and upcycling is one approach that may contribute to the food loss reduction targets. Second, we investigate if acceptance of upcycled plant-based protein depends on if NBT such as gene-editing are used in the upcycling process. We thus contribute with insights on consumer acceptance and the market reception for food developed by gene-editing, and this feeds into an ongoing policy debate. The position in EU regarding NBT has largely reflected consumer attitudes on the matter (Qaim, 2020). The European Commission recently presented a proposal regarding certain types of gene editing, suggesting that crops developed by those techniques are treated as traditionally bred crops, not requiring additional risk assessment, traceability or labelling. Third, we relate the insights on consumer acceptance and market predictions to which consumers that are likely to purchase upcycled plant-based protein. This is important for gaining insights on the actual environmental benefits such products may contribute with. To exemplify, if upcycled plant-based products mainly appeal to vegetarians/vegans, the environmental benefits will be relatively narrow, while if a significant share of non-vegetarians can be expected to purchase the upcycled potato-protein products, the sustainability improvements will be important.

2. Background

2.1. Side-stream in potato starch production upcycled to food

Potato is among the most widely grown crops globally (Waglay and Karboune, 2016), where 55 million tonnes of potatoes were harvested in EU in 2020 (Eurostat, 2021). The potato-protein end up in a side-stream in the starch production (Bartek et al., 2022), and while the protein content is limited to approximately 1.5–2 per cent (Camire et al., 2009; Waglay and Karboune, 2016), the yields of potatoes harvested for starch production imply large amounts of an available protein resource. This source of protein has favourable traits compared to other sources of plant protein, as the biological value of potato protein makes it nutritionally comparable to soy and eggs (Camire et al., 2009), while it is low-allergen compared to several other vegetable protein sources, including egg, soy, nut and gluten (Waglay and Karboune, 2016). At present the protein is mainly used for animal feed, fertilizer or thrown away directly (Fu et al., 2020), and one reason for this is that the side-stream in which the protein end up also contains toxic substances, and removing those requires high use of energy and use of chemical protein-cleansing processes (Hussain et al., 2021). An alternative to the energy intensive and thus costly chemical protein-cleansing processes is to use gene-editing to remove the toxic substances in potato-protein (Bartek et al., 2022; Zheng et al., 2021). As found in an LCA analysis, compared to current practice, where the protein in the starch production side-stream is mainly used as feed and fertilizer, using the gene-edited protein for human consumption has significant environmental benefits, particularly with respect to global warming, terrestrial acidification and land use (Bartek et al., 2022). The use of potato-protein as an ingredient is approved under the EU Novel Food Regulation (Alting et al., 2011), while the regulatory status of the gene-edited variant currently also falls under the regulation of GMO crops in EU.

2.2. Consumer acceptance of upcycled food

Insights regarding consumer perception and acceptance of upcycled food ingredients is field of research that has developed in recent years. The communication regarding upcycled food products influence the associations that it invokes among individuals towards such products (Aschemann-Witzel et al., 2023), where emphasizing positive impacts on health, nutrition, sustainability, food waste reduction, and the economy is associated with higher acceptance (Lu et al., 2024). Perceived usefulness and level of innovation increase acceptance of technology behind upcycled food (Hellali and Korai, 2023). Consumers tend to accept upcycled food more when the product is from a vice category such as cookies compared to a virtue category such as sandwiches (Peschel and Aschemann-Witzel, 2020). The degree of processing also impact acceptance, where a field experiment in the Netherlands finds that upcycled pumpkin is more accepted when sold in a more transformed state (pureed vs. sliced) (de Visser-Amundson et al., 2023). Consumer psychographic characteristics have also been found to influence acceptance of upcycled foods (Lu et al., 2024), where food neophobia is associated with lower degree of acceptance (Aschemann-Witzel et al., 2022) and lower purchase intention of upcycled food (Coderoni and Perito, 2020), and environmental concern is associated with a higher acceptance of upcycled foods (Altintzoglou and Aschemann-Witzel, 2024; Aschemann-Witzel et al., 2022; Coderoni and Perito, 2020; Grasso and Asioli, 2020).

While less common, a few studies investigate consumer willingness to pay for upcycled food compared to traditional food. Bhatt et al., (2020) found that consumers are willing to pay less for upcycled food compared to conventional products, although the difference can decrease with more rational (not emotional) communication on the advantages of the product. Asioli and Grasso (2021) similarly found that information about environmental and health benefits with upcycling resulted in a higher willingness to pay for upcycled biscuits among respondents in UK, although conventional biscuits remained preferred. Hellali et al., (2023) find that consumers in Canada are willing to pay less for upcycled versus conventional food products, and that this difference is larger for risk-averse individuals. Emphasizing environmental or health benefits has a greater effect on the willingness to pay compared to those centred on the economy. Kawata and Kubota (2018) find that the willingness to pay for reprocessed chicken, that was prepared from meat close to expiry date, was around 90 % of the price for conventional chicken among Japanese consumers. Preferences for upcycled food compared to conventional is lower when the upcycled ingredient results from a more radical innovation such as potato chips made from waste from the sunflower oil industry compared to smaller and more familiar innovations such as fruit juice made from recovered fruits and vegetables (Hellali et al., 2023).

2.3. Consumer acceptance of gene-edited food

There is research to suggest that consumers are more willing to accept and consume food developed by genome-editing compared to transgenic GMO methods, although traditionally bred crops remain most preferred (Beghin and Gustafson, 2021; Hu et al., 2022; Marette et al., 2021; Muringai et al., 2020; Ortega et al., 2022; Shew et al., 2018; Uddin et al., 2022; Yang and Hobbs, 2020). Further, acceptance of NBT, including intragenesis and cisgenesis, where genes are transferred only between related organisms, has been found to increase when the crop is developed with sustainability traits, such as enabling reduced pesticide use (Edenbrandt et al., 2017; Muringai et al., 2020; Paudel et al., 2023) or fungicide use (Delwaide et al., 2015), as well as food quality traits (Edenbrandt et al., 2018; Hu et al., 2022).

3. Material and methods

At the time of data collection, in EU, crops developed by NBT, including CRISPR-Cas9, fell under the regulations for GMO crops, which implies separate testing and approval processes compared to traditionally bred crops. Few crops are currently approved for cultivation in Europe (Purnhagen and Wesseler, 2021; Turnbull et al., 2021). Therefore, a discrete choice experiment (DCE) was used to collect data on consumer preferences with regard to the potential acceptance of crops and products based on CRISPR-Cas9 because these products are currently not marketed within the EU.

3.1. Data collection and participants

Data were collected from a representative sample of 1,508 Swedish consumers from a consumer panel managed by PFM Research during September 2023, using a web-based survey. Participation in the panel and in the survey was voluntary; respondents were informed about the purpose of the study, and they could withdraw at any point without giving a reason. Prior to entering the survey, participants gave their consent. Respondents were rewarded by the panel firm in the form of points that can be transferred to vouchers. Panel members received an invitation to participate in the survey with a personalized link, which prevented them from answering more than once. The invitation to participate in the survey did not describe the purpose of the study (only that it concerned food habits and preferences) to reduce the potential selection bias of including individuals with special interest in gene editing and/or meat substitutes (Aguinis et al., 2021; Newman et al., 2021). The survey was distributed in Swedish, and all panel registration procedures were performed in Swedish, avoiding professional respondents from other countries (Aguinis et al., 2021). No sensitive personal information about the participants was collected, and this type of study and data collection does not require approval according to the Swedish Ethical Review Authority (2021).

We applied quota-based sampling to match the population with respect to age and gender. Respondents that indicated that they were not responsible for food purchase to at least some degree were screened out (62 such cases were excluded). Moreover, to ensure that the respondents payed attention, respondents that failed to provide the correct response to a trap question were screened out (100 were excluded for this question). Finally, respondents with a response time below 3 min were excluded from analysis, as testing prior to data collection deemed this an unrealistically fast response time if they respondents were to read the questions. Descriptive statistics of the sample are presented in Table 1.

3.2. Experimental design

The experiment included one control group and two treatment

Table 1
Sample characteristics.

	Pooled	Control	Upcycled-chemical process	CRISPR-Cas9	Diff.
Number of participants	1508	515	494	499	
Gender (%)					
-males	49.5	50.8	47.57	50.1	ns
-females	49.9	48.6	52.23	48.9	
-non-binary	0.6	0.6	0.2	1.0	
Education (%)					
-elementary school	40.2	42.7	39.5	38.3	ns
-high school	25.9	25.8	25.3	26.5	
-university level	34.0	31.5	35.2	35.3	
Age					
-age (mean)	49.0	49.0	48.8	49.1	ns
-age(sd)	17.0	17.2	16.9	17.0	
18–34	29.4	29.9	29.0	29.3	
35–59	39.9	39.6	39.7	39.9	
60-	30.9	30.5	31.4	30.9	
Income					
-income SEK (mean)		52,500	53,947	52,445	ns
-income (sd)		27,328	26,689	26,689	
Household					
-size (mean)	2.4	2.5	2.4	2.4	ns
-single households (%)	25.7	26.2	25.5	25.3	ns
Dietary preferences (%)					
-flexitarian/ pescitarian	11.3	9.9	9.9	14.0	ns
-vegetarian/vegan	2.5	2.9	2.6	1.8	ns
Completion time (median) (minutes)	8.0	7.9	8.2	8.0	

groups. The information provided prior to the first choice task varied between the three groups (Survey overview is provided in Supplementary Material, Fig. S1). All participants were informed that potatoes can be used for direct consumption, starch production and as a protein used in food to produce for example meat-substitutes.[1] The control group was not provided any additional information, while participants in the 'Upcycled' treatment group were informed that the protein is not suitable for human consumption due to the toxic compounds, and is currently used for feed or wasted. However, with chemical cleaning it can be made suitable for consumption and choosing potato protein products contributes to reduced food waste. Likewise, participants in the 'CRIPSR-Cas9′ treatment group were informed that with new gene editing technologies called CRISPR-Cas9, the toxic compounds can be removed. The information aimed to be non-technical and clear, while providing sufficient information for respondents to make informed choices, in line with previous studies on NBT (Delwaide et al., 2015; Muringai et al., 2020). While not possible to be certain about the degree that participants fully understand information provided in surveys and experiments, we understood measures to increase the likelihood that respondents read and understood the information. A follow up question was posed regarding the key message of the information treatment. The rate of correct responses was 95 per cent for the control group, and 96 percent for the 'CRIPSR-Cas9′ treatment group, while lower (76 per cent) for the upcycled group. Importantly, all respondents that failed this question were informed about the correct response before proceeding with the choice tasks. The information and following questions are presented in Appendix A1, while summary statistics for the choice tasks are included in Section S1.

Sausage was selected as the product category in the DCE since it is a widely purchased product category with both meat-based and plant-based variants available. The types of sausages included in the DCE, and the attributes that described them, were selected based on the current market situation and from a pre-survey (September 2020, N = 497), where respondents indicated the most important attributes when purchasing sausages. We wanted to include protein alternatives that are the main types currently on the market (meat and soy), as well as relevant substitutes to a domestically produced protein (pea). A key attribute of meat-based sausages is the meat content, where higher meat content is associated with higher quality. For this reason, we included meat-based with high share of meat (75 per cent), reflecting a premium type of sausage, meat-based with a low share of meat (55 per cent), plant-based sausages based on soy-protein, pea-protein and potato-protein, as well as an opt-out alternative.

Each product was described by the country of origin of the protein source (domestic or other EU country for meat, pea and potato, other EU country or Brazil for soy). We note that while it is mandatory to display the country of origin for meat, this is not the case for plant-based meat substitutes, and this is often not displayed clearly on the packages. Yet, we included country of origin for this in the experiment to enable us to investigate preferences regarding this. The products were also described by production method, where we used the domestic "KRAV" logo to indicate organic. Price levels were selected based on market prices. The choice tasks, as illustrated in Fig. 1, used a graphical display of the product with the attributes and levels as indicated in Table 2.

The DCE included five labelled alternatives and an opt-out alternative, and the design was generated using a d-efficiency criterion, with priors from the pre-study. The main effects design included 18 choice tasks, which were divided into blocks of two to reduce the number of tasks for each respondent, such that each respondent was randomly assigned to one of the blocks with nine choice tasks.

[1] Products with the potato-protein are not widely available in the Swedish market (we are not aware of any products), although there is a large starch producer in the Netherlands that sell protein for human consumption to food processors.

4. Data analysis

According to Random Utility Theory (McFadden, 1974), the utility from a product comprises a systematic component, the indirect utility V, and a random error component, ε. Individuals are assumed to derive utility from the characteristics of a product, and to choose the product among a set of alternatives that provides the greatest utility. For individual n, the utility of alternative $i = 1,\ldots,J$ is $V_{ni} = \alpha_i + \beta X_{ni}$, where α_i is an alternative-specific constant, indicating the utility for sausage type i relative to the base level, which is normalized to zero for identification purposes. β is a vector of taste parameters to be estimated, and X represents the attributes associated with the product faced by the individual. The error terms are assumed to be Type I extreme value distributed with variance $\sigma^2 = \pi^2/6\lambda^2$, where λ is a scale parameter that is normalized to unity. This assumption implies that the difference in the error terms is logistic, resulting in the multinomial logit (MNL) model (Train, 2009).

To account for unobserved preference heterogeneity, while relaxing the IIA assumption in the MNL model, and accounting for the repeated choices by respondents in this study, we estimate mixed logit (ML) models (Hensher et al., 2015; Train, 2009). We specify the model such that there is preference heterogeneity between individuals, while assuming stable preferences for each individual. We specify the alternative specific constants (sausage type and the no purchase option) as random parameters with normal distributions and the price coefficient to take a negative lognormal distribution. The random taste parameters are described by a density function $f(\alpha)$, which takes the form $\alpha_{ni} = a_i + \sigma_i e_{ni}$ for individual n and product i, with the population mean a, the parameter standard deviation σ, and the random error term $e_{ni} \sim$ i.i.d. N(0,1) (Train, 2009). The unconditional probability of individual n's sequence of T choices is:

$$P_{ni} = \int \left(\prod_{t=1}^{T} \left[\frac{\exp(\lambda V_{nit})}{\sum_{j=1}^{J} \exp(\lambda V_{njt})} \right] \right) f(\alpha|\mathrm{a}, \sigma) d\alpha \tag{1}$$

The utility specification is included in Appendix. The parameters are estimated by using the maximum simulated likelihood method, since the probability function has no closed form solution (Train, 2009). Models were estimated with 1000 Sobol draws, using the Apollo package in R (Hess and Palma, 2019).

To explore the first and second objectives of the study, we should compare preferences and demand for the upcycled potato-protein product and if this varies across the control and treatment groups. The estimated parameters are confounded with λ, which disables direct comparison of parameters across samples (treatment groups). Willingness to pay (WTP) is obtained from the ratio of the preference parameters and the negative price parameter, and given that this is a ratio, the scale parameter cancels out, which enables comparisons of WTP across the treatment groups.

The estimates from the ML models were used to make market predictions following the implementation of potato-protein sausages. Specifically, the estimated coefficients from the ML models were inserted into the probability Eq. (1), while specifying the attribute levels and prices. This enabled us to retrieve market shares for the different products, and importantly, to explore the substitution patterns that arise if the potato-protein-based sausage is introduced, when derived from upcycled protein and when developed by CRISPR-Cas9 technology.

To explore the third objective, regarding which consumers that are most likely to accept the upcycled and CRISPR-Cas9 developed protein product, we derived posterior estimates based on the estimates in the ML model, following the procedure in Train (2009). This provides posterior parameters for each subpopulation with a certain sequence of choices (often referred to as 'individual-level parameters'), which enables us to explore heterogeneity in preferences. We regress the posterior preference parameters on personal characteristics of the individuals and dietary preferences.

Fig. 1. Example of choice task. Note: Pictures were displayed vertically (in randomized order) to ensure a presentation format also suitable for mobile phones.

Table 2
Attributes and levels in the discrete choice experiment.

	Alternatives. Sausages made from:				
	Meat (75 %)	Meat (55 %)	Soy	Pea	Potato
Attributes					
Production method	conventional, organic	conventional, organic	conventional, organic	conventional, organic	conventional, organic
Country of origin (protein)	Sweden, other EU country	Sweden, other EU country	Other EU country, Brazil	Sweden, other EU country	Sweden, other EU country
Price [a]	32,44,56, 68,80,92	22,32,42, 52,62,72	22,32,42, 52,62,72	22,32,42, 52,62,72	22,32,42, 52,62,72

[a] Price per package of 400 g (SEK) At the time the study was conducted, 10 SEK ~ €0.84.

Based on the posterior parameters, we calculated the welfare effects from introducing the upcycled and gene-edited potato-protein product to the market. We estimated the compensating variation, which is the difference between the expected utility after the gene-edited potato-protein product is implemented (V_1) and the current market situation (V_0), normalized by the marginal utility of income. This is obtained using the log-sum formula (Small and Rosen, 1981; Train, 2009):

$$CV_n = \frac{1}{\gamma_n}\left\{ ln\sum_{j=1}^{J^1} e^{V_n^1} - ln\sum_{j=1}^{J^0} e^{e^{V_n^0}} \right\} \quad (2)$$

where γ_n is the negative cost parameter, which is the marginal utility of income; J^1 is the choice set in scenario 1; and J^0 is the choice set in the current market situation.

5. Results

In a first step, we estimated both separate ML models for the control and treatment groups and a model where the samples are pooled, while controlling for differences in scale across the groups (Swait and Louviere, 1993). An LR test suggested that there are statistically significant differences between the treatments (LR-statistic[2] = 98.76; d.f. 32; P ($\chi^2 \leq 46.19$) = 0.05). For this reason, we proceed with separate models for the treatment groups. For all treatment groups, meat is preferred over all meat substitutes, where the high quality meat sausages (75 percent meat content) is the most preferred meat sausage type (Table 3). Further, among the meat substitutes, soy is the least preferred, followed by pea based while the potato-protein based sausages are the most preferred meat substitute sausages. It is noteworthy that this holds in all treatment groups, meaning that consumers prefer the potato-based meat substitute over soy and pea, also when being aware that it is derived from upcycled ingredients and developed by CRISPR-Cas9 technology. However, the relatively large standard deviations for the meat substitutes implies that there is substantial variation among consumers.

The results further show that consumers prefer sausages based on domestic over imported meat. The same holds for the plant-based sausages, although the country of origin is less important for these products. Likewise, EU-produced soy is preferred over Brazilian soy. Furthermore, organic production is preferred over conventional, although this attribute is less important than the country of origin.

While the same patterns appear within all treatment groups, to facilitate comparison across treatment groups, we present WTP estimates in Table 4. The WTP for potato-protein based sausages over meat is significantly higher in the control group than in the upcycled and CRISPR-Cas9 treatment groups. While the WTP is less negative in the CRISPR-Cas9 treatment than in the upcycled treatment, this difference is not statistically significant. Interestingly, the WTP for organic production and domestic meat is higher in the upcycled treatment. This could potentially be related to the chemical process mentioned in the upcycled information treatment regarding how the potato-protein in the side-stream can be made edible.

Based on the estimates in Table 3, we calculated market share predictions for the different product types before and after the potato-protein product would be introduced on the market. Stated preference methods are associated with limitations for predicting actual market shares, due to hypothetical nature of the choices, to omitted variables in the experiment that may be important in the market situation, and that it facilitates product combinations that are not available in the market due to correlations between attributes. However, market predictions from stated preference data are informative for investigating changes in

[2] The LR-statistic is computed as $-2*(LL_{Pooled} - (LL_{Control} + LL_{Upcycled} + LL_{Gene\text{-}scissors})$, and the degrees of freedom is $K_{Control} + K_{Upcycled} + K_{Gene\text{-}scissors} - K_{Pooled}$.

Table 3
Mixed logit model estimates.

Sausage type[a]	Control		Upcycled		CRISPR-Cas9	
	Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
Meat (75 %)	1.10	1.31	1.10	1.31	1.09	1.10
	(12.10)	(9.94)	(12.16)	(10.43)	(13.58)	(9.49)
Soy	−4.03	3.55	−4.59	5.13	−4.47	4.40
	(10.31)	(13.79)	(9.06)	(9.02)	(10.80)	(10.91)
Potato	−1.95	3.48	−2.77	3.65	−2.90	4.20
	(7.55)	(5.07)	(8.93)	(9.41)	(9.56)	(12.57)
Pea	−3.52	3.52	−3.55	3.57	−3.61	3.45
	(9.11)	(9.57)	(10.02)	(9.86)	(10.63)	(13.48)
Don't purchase	−5.64	4.10	−4.76	3.78	−5.94	4.67
	(9.95)	(8.53)	(12.7)	(12.32)	(11.95)	(11.46)
Product attributes						
Organic production	0.26		0.40		0.38	
	(6.40)		(8.40)		(7.84)	
Meat: Domestic (EU = ref.)	1.38		1.44		1.29	
	(13.37)		(13.02)		(12.61)	
Soy: Brazil (EU = ref.)	−0.58		−0.75		−1.06	
	(2.47)		(3.02)		(4.55)	
Potato: Domestic (EU = ref.)	0.66		0.87		0.88	
	(4.30)		(4.49)		(5.24)	
Pea: Domestic (EU = ref.)	1.28		1.13		0.96	
	(7.18)		(5.92)		(5.47)	
Log(Price)	−3.16	0.86	−3.32	1.04	−3.09	0.99
	(41.62)	(6.85)	(41.7)	(18.61)	(37.92)	(24.55)
Mean price/St.Dev price	−0.06	0.07	−0.06	0.12	−0.07	0.13
# Individuals	515		494		499	
# Observations	4635		4446		4491	
LL	−5399.69		−5016.5		−5021.44	

Note: Numbers in parenthesis are |t-values|.
[a] Meat 55 % meat content is the reference alternative.

Table 4
Willingness to Pay estimates.

	Control (C)	Upcycled (U)	CRISPR-Cas9 (CC)	Differences across treatments [a]		
				C=U	C=CC	U=CC
Sausage type:[b]						
Meat (75 %)	37.75	51.79	38.93			
	[28.39; 49.78]	[39.55; 66.04]	[30.55; 49.09]			
Soy	−137.82	−214.67	−158.88	*		
	[−183.05; −102.37]	[−277.36; −160.05]	[−204.28; −120.18]			
Potato	−66.66	−130.23	−103.14	**	*	
	[−94.74; −44.64]	[−173.68; −94.00]	[−135.51; −75.69]			
Pea	−121.46	−168.21	−129.21			
	[−173.18; −82.39]	[−219.03; −127.23]	[−162.36; −100.52]			
Organic	9.09	19.12	13.79	**	*	
	[6.05; 12.81]	[13.72; 25.45]	[9.89; 18.38]			
Meat: Domestic	47.82	68.24	46.52	*		*
	[35.94; 63.46]	[52.39; 87.11]	[35.92; 58.66]			
Soy: Brazil	−19.96	−35.58	−37.82			
	[−38.52; −3.70]	[−62.26; −11.33]	[−56.17; −21.11]			
Potato: Domestic	23.06	41.15	31.45			
	[12.01; 36.71]	[22.63; 62.65]	[19.02; 45.36]			
Pea: Domestic	44.31	53.90	34.49			
	[29.27; 63.48]	[33.85; 77.04]	[21.52; 48.87]			

Note: Numbers in brackets are 95 percent confidence intervals. WTP estimates are obtained with Krinsky and Robb method with 10,000 repetitions.
[a] Test for differences based on Poe test. * indicates if $p < 0.05$, ** if $p < 0.01$, and *** if $p < 0.001$.
[b] Meat (55 %) is the reference alternative.

market shares under different scenarios (Hensher et al., 2015), and this is the purpose of the following analysis, where we focus on how consumers are expected to react to the introduction of a new product type.

The baseline scenario includes four types of sausages: meat share (75 per cent), meat (55 per cent), pea-protein based and soy-protein based. Prices are set at the median in the choice experiment, which were selected around the current market prices for sausages. The meat and pea based sausages are produced domestically, while the soy-based sausage is produced in another EU country. All products are conventionally produced.

In the second scenario, the potato-protein-based sausage is introduced, priced at the median, produced domestically using conventional production methods. The market shares under the two scenarios are reported in Fig. 2 for each treatment group.

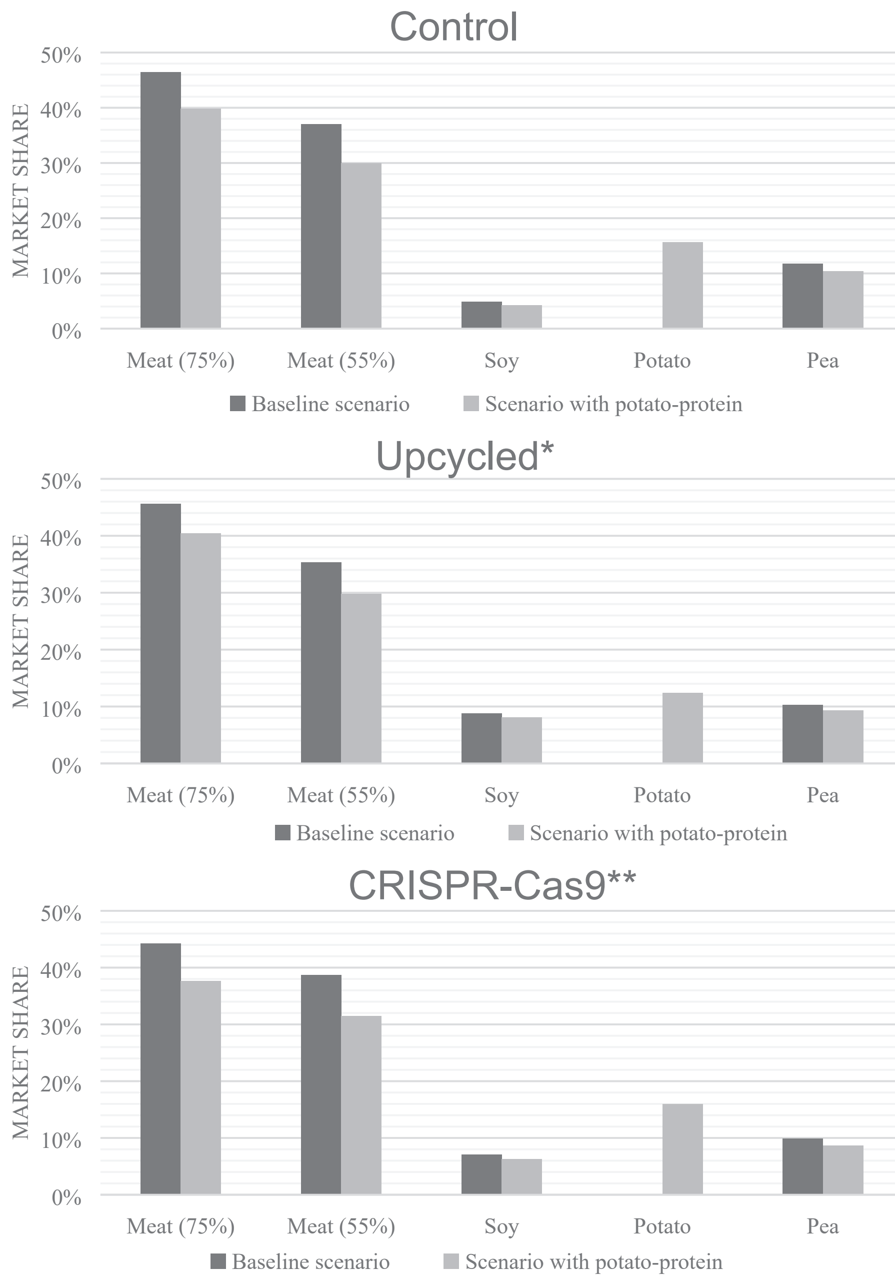

Fig. 2. Predicted market shares before and after a market introduction of potato-protein based sausages by treatment group. * Upcycled = potato-protein is an upcycled ingredient derived by chemical processing. **CRISPR-Cas9 = potato-protein is an upcycled ingredient derived from gene-edited potato.

In the baseline scenario, the meat-based sausages hold the largest share of the market (83 per cent in the control and CRISPR-Cas9 treatment, 81 in upcycled treatment), where the high meat content variant has the largest market share. The remaining market shares are divided between soy and pea, where pea holds the larger share.

Our main interest lies in the changes in market shares following the introduction of the potato-protein. Fig. 2 shows that the potato-protein-based sausages claim a substantial market share in the control group and CRISPR-Cas9 group (16 per cent), while it is 12 per cent in the upcycled group. Importantly, comparison to the baseline scenario shows that the main part of the market share for the potato-protein-based sausages are a result of substitutions away from meat and, to a lesser degree, away from soy and pea. The meat-based variants decline by around 14 percentage points in the control and CRISPR-Cas9 group and 11 percentage points in the upcycled group, while the plant-based variants declines by 2 percentage points.[3] We note that the market share for plant-based products is considerably larger than the share of vegetarians/vegans in the sample (2.4 per cent) and flexitarians (11.3 per cent). This implies that the implementation of potato-protein that is made from upcycled ingredients and that is developed by CRISPR-Cas9 technologies can

[3] The predicted market shares reported in Fig. 2 are conditional on choices made in the DCE, implying that it does not take the no-purchase option into account. The predicted market shares that are unconditional on choice provide similar results, suggest small changes in the share that 'do not purchase'.

potentially contribute to the shift towards more plant-based diets. Currently, meat sausage consumption in Sweden is approximately 53.1 million kg (calculations based on Amcoff et al., (2012.) While we do not have access to data on the market size for plant-based sausages, the market shares from the baseline scenario in Fig. 2 implies that the total market for sausages in Sweden is 64.0 million kg. The implementation of upcycled and CRISPR-Cas9 developed potato sausages, priced equally as soy, pea and low-meat sausages, would imply demand for 10.2 million kg of potato-protein based sausages. Assuming that the share of potato-protein in the sausages is 65 per cent, the demand for potato-protein will be 6.6 million kg. We note that the estimated demand is in the same size range as the current amount of potato-protein resulting from the side-stream in starch production in Sweden (6.1 million kg). Importantly, the predicted decrease in demand for meat-based sausages, from 83 percent to 69 percent (CRISPR-Cas9 group in Fig. 2), implies a reduction of approximately 8.9 million kg of meat-based sausage consumption, or 5.8 million kg meat, given 65 per cent meat content on average. Taken together, the replacement of meat, with plant-based protein that is currently not used for human consumption, is predicted to result in significant environmental benefits. More details on the calculations are provided in Section S2.

The expected welfare gain (or loss) associated with the introduction of the gene-edited potato protein sausage is calculated using the posterior parameters. The estimated compensating variation represent respondents' average WTP to move from the current scenario (no potato protein sausages) to the new scenario (upcycled and CRISPR-Cas9 developed potato-protein-based sausages available). This is estimated to result in an average compensating surplus of 3.18 SEK (€0.27) per purchase situation when they are aware that the product is derived from a gene-edited potato. Assuming that meat purchases consist of 400 g packages, and that the market share of meat substitutes that is obtained in the baseline scenario in Fig. 2, the total number of sausage purchases made in Sweden annually is 164 million. This implies an annual welfare gain of approximately €4.2 million.

To explore how the preferences for the different product types relate to consumer characteristics, we regressed the posterior preference parameters on age, gender, education level and diet in the form of dummy variables for vegetarians/vegans and flexitarians. Results are reported in Table 5, where the dependent variable is the preference for the potato-protein sausage compared to the baseline product (meat 55 per cent). Results for the other products are reported in Table S1–S3. The negative coefficient for age in the CRISPR-Cas9 model implies younger individuals are less negative towards potato-protein sausages compared to meat increases. Over all, the personal characteristics are poor predictors of the preferences, while dietary habits are important predictors. As could be expected, individuals who are vegetarian/vegan are more positive towards potato-protein based sausages over meat than non-vegetarians, and the same holds for flexitarians, although to a smaller extent.

Table 5
Linear regression of individual characteristics on conditional estimates for potato-protein.

	Control	Upcycled	CRISPR-Cas9
Intercept	−1.85	−2.22	0.04
	(−1.88)	(−2.51)	(0.04)
Female	0.36	0.13	0.31
	(1.67)	(0.63)	(1.30)
Age	−0.01	−0.02	−0.13
	(−0.33)	(−0.71)	(−2.70)
Age^2	−0.00	−0.00	0.00
	(−0.23)	(−0.05)	(1.87)
Low education	−0.36	−0.26	−0.42
	(−1.38)	(−0.97)	(−1.43)
High education	−0.04	−0.29	0.37
	(−0.12)	(−1.09)	(1.16)
Flexitarian	2.86	2.88	3.01
	(6.49)	(6.32)	(6.61)
Vegetarian/vegan	4.67	4.94	6.03
	(7.90)	(6.78)	(10.35)
N	509	493	494
R^2	0.24	0.24	0.29

Note: Dependent variable is conditional estimate of potato-protein, which is obtained from the ML model in Table 2. Meat (55 per cent) is the base level. t-statistics in brackets.

6. Concluding discussion

Targeting food loss at the production stage, by transforming it to food (upcycling) can contribute to increased agro-environmental sustainability. Vast quantities of high quality protein is produced, found in the side-stream of potato-starch production, but is currently mainly wasted or used for animal feed. The protein in the industrial side-stream can be made suitable as food through chemical processes. Alternatively, CRISPR-Cas9, a form of gene-editing, facilitate precise breeding and can introduce traits that enable the extraction of potato-protein without chemical processes.

This paper investigates how upcycling of potato-protein can contribute to reduced food loss and shifts in food consumption towards more plant-based protein, and if the acceptance of upcycled food products depends on the process (chemical process vs. gene editing). We use a discrete choice experiment with potato-protein based sausages and key product variants currently on the market (sausages made from meat, soy and peas). Our results show that most consumers prefer meat-based sausages over plant-based variants, which is in line with previous empirical studies (Edenbrandt and Lagerkvist, 2021; Van Loo et al., 2020). The potato-protein product is the most preferred plant-based sausage, followed by peas and soy.

The results suggest that the WTP for potato-protein sausages is significantly lower when upcycled using a chemical process, which corroborate previous studies that find a lower willingness to pay for upcycled food products (Bhatt et al., 2020; Hellali et al., 2023). We concur that our findings could be related to the chemical process required to extract the potato-protein and remove toxic substances that are present in the side-stream. Our results relate to those in Hellali and Korai (2023), which shows that a higher level of innovation for upcycling is associated with a lower level of perceived usefulness of upcycling as a method to reduce food waste. Further, while research on attitudes, liking, willingness to eat and perceptions of upcycling of food is emerging (Aschemann-Witzel and Stangherlin, 2021; Grasso et al., 2023; Lu et al., 2024), we contribute with an economic approach, measuring preferences and predicting purchase behaviour.

As a key contribution, we compare preferences for upcycling obtained through adoption of gene-editing technology to enable the extraction of the food grade potato-protein, with those where chemical processes condition upcycling. Notably, using gene-editing for upcycling of potato-protein does not further decrease the WTP for the product as compared to when chemical processes are used. This result suggests acceptance of this new breeding technology, at least among consumers that are willing to purchase plant-based sausages. However, there is a lower willingness to pay for the upcycled and gene-edited potato-product compared to the conventional product, and this is in line with a number of studies among consumers in China (Ortega et al., 2022), Canada (Muringai et al., 2020; Yang and Hobbs, 2020), USA (Hu et al., 2022), as well as across different countries (Marette et al., 2021; Shew et al., 2018). While there is evidence of food technology neophobia being negatively related to the acceptance of upcycled food (Coderoni and Perito, 2020; Lu et al., 2024), we are not aware of any study that investigates if the technology for transforming waste to food, in this study gene-editing, affects the willingness to pay for upcycled food products.

As a further contribution of this study, we investigate the implications from our results by predicting the market potential for the upcycled plant-based product. In a baseline scenario, reflecting the current market situation where potato-protein based sausages are not available, we find that, holding prices constant, approximately 80 percent are predicted to choose a meat-based sausage. In the scenario where the potato-protein-based sausage developed by gene-editing is introduced, this product is predicted to gain a market share of 16 percent, and the main part of this market share is a result of substitutions away from meat and, to a lesser degree, away from soy and pea. Personal characteristics such as gender, age and education are not important predictors of the willingness to pay for the potato-protein-based sausage relative to the meat-based alternative, while being a vegetarian/vegan or flexitarian are important predictors.

A key finding from this study is that the predicted market share for potato-protein is significantly larger than the share of vegetarian/vegan individuals in the sample. Hence, the introduction of upcycled meat-substitutes based on potato-protein hold potential to contribute to significant environmental benefits by substitutions away from meat.

Our study is based on hypothetical purchases, given the lack of real products on the market. While non-availability motivated the choice of a stated preference method, an experiment where real products are included would be interesting for future research. For example, it would be valuable to investigate how demand is affected when individuals are able to consume the NBT product. Such studies will be made possible as the breeding developments and approvals progresses. Another limitation with this study is that while we tested respondents' comprehension of the information that was provided prior to the experiment, it is not certain to what degree they fully understood the technology described.

Another interesting venue for future research is to elicit consumer preferences for products where the CRISPR-Cas9 developed potato-protein is included in more processed products. Asioli et al. (2017) concluded that naturalness in food is considered an aspect of non-GMO, and that the degree of processing is an important factor that drive consumer preferences for natural food. De Visser-Amundson et al. (2023) found that less processed upcycled ingredients are more accepted. Future studies may explore whether acceptance for upcycled ingredient enabled by gene editing is different when used as an ingredient to increase the protein content (such as a ready meal) compared to the plant-based protein product, where the CRISPR-Cas9 potato-protein is the main ingredient.

6.1. Policy implications

Several policy implications stem from the findings in this study. First, they provide support for consumer's acceptance and willingness to purchase upcycled food products. We find that the potential contribution of using upcycled crop side-streams as an input to plant-based meat substitutes to reduced food loss is substantial. Although consumers are willing to pay less for products with upcycled crop ingredients, our results imply that meat-substitutes with upcycled ingredients are predicted to gain a significant market share, resulting from substitutions away from meat and imported soy. Considering the importance of reducing food loss and waste, policy makers should accommodate the use of upcycled ingredients in food production, as this is an area that holds great potential from a sustainability perspective. For example, the implications for individuals firms of using food-to-waste side-streams is not obvious, and it is often more profitable and easier to continue as usual rather than adopting upcycling in the production (Altintzoglou and Aschemann-Witzel, 2024). An important task for policy makers is thus to motivate food producers to reduce loss and increase efficiency by upcycling side-streams. From a policy perspective, efforts that encourage public and private initiatives that accommodate upcycling in the different stages of food production may contribute to increased use of side-streams in the food industry. One potential venue for increased use of side streams could be to facilitate mapping of available resources, assisting in the matching of producers of side-streams and potential buyers that can use such side-streams in their food production. Further, policy makers may consider possibilities to reduce logistical hurdles with respect to using side-streams in new production facilities.

Second and importantly, the results from this study suggest that the market potential for upcycled plant-based protein findings hold when the upcycled ingredient is derived through gene-editing. Given that gene-editing can enable upcycling of potato-protein while avoiding the otherwise necessary use of chemical processes in the protein extraction (Bartek et al., 2022), the acceptance of this technology is promising from a sustainability perspective. A major hurdle to the realization of these market-based sustainability improvements is the current legal status of NBT, including gene-editing and CRISPR-Cas9 specifically within the European Union. The hitherto legal framework in EU has largely reflected the concerns and low acceptance among citizens (Qaim, 2020), although there has been much debate with respect to regulations of NBT (Purnhagen and Wesseler, 2021). Following a decision by the European Commission in 2018, the legal status for NBT is the same as for transgenic GMO in EU (Turnbull et al., 2021). Recently, a proposal from the European Commission suggests that certain new genomic techniques are treated as crops bred with traditional methods, and thus not demanding labelling, traceability or additional risk assessments (European Commission, 2023b). The new policy proposal is supported in this study, as we find a high acceptance of gene-edited food, at least among consumers that are willing to purchase meat substitutes. The results further point to the importance of the NBT being used to develop crops that target significant improvements with respect to sustainability, while being in line with evolving consumer demand. It is further key from a policy perspective to identify administrative hurdles in this process.

Taken as a whole, our findings suggest that future policies should attempt to reduce barriers for using side-stream products in food. Accommodating NBT has the potential to enable the use of currently unobtainable and wasted side-streams in food production, and any regulations that jeopardize the use of such sources will results in significant welfare losses.

CRediT authorship contribution statement

Anna Kristina Edenbrandt: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Carl-Johan Lagerkvist:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodpol.2024.102665.

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