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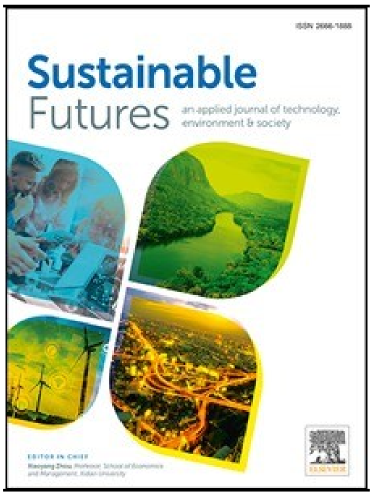

Farmers' Attitude towards Green Ammonia Produced by Upcycling Waste Nitrogen: Empirical Evidence from an Iowa Study

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Highlights

- A survey on Iowan crop growers was used to elicit acceptance of green ammonia.
- Survey finds 48% of crop growers mainly use ammonia as nitrogen fertilizer.
- Data shows favorable attitude (50%) towards using green ammonia as a fertilizer.
- A lower level of support (32%) of green ammonia as a fuel was observed.
- Socioeconomic and psychological factors affecting acceptance was assessed.

Farmers' Attitude towards Green Ammonia Produced by Upcycling Waste Nitrogen: Empirical Evidence from an Iowa Study

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Abstract

This study examines farmers' acceptance of green ammonia produced by upcycling waste nitrogen using renewable energy. A mail survey, targeting a random sample of crop growers in Iowa, USA, found moderately high acceptance: about 50% support green ammonia as a fertilizer and 32% support green ammonia as a fuel. Support for green hydrogen is only 17% (24% opposing), demonstrating a preference of 2nd-generation over 1st-generation technologies. Ordinal logistic regression reveals social and psychological factors affecting attitude, including income, ideology, perceived benefit, ammonia usage, trust in science and technology, personal belief in reducing waste nitrogen, and social norm.

Keywords: Green ammonia, Acceptance, Survey, Waste nitrogen, Green hydrogen, Renewable energy

Acknowledgements.

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1. Introduction

Ammonia (NH_3), a compound containing nitrogen and hydrogen, has been widely used in the production of fertilizers and industrial chemicals (1). Ammonia can also be used as a renewable fuel (2), because it is a good energy carrier as well as a convenient hydrogen bearer (3,4). Currently, ammonia is made from fossil fuels (mainly natural gas and coal) with 2 tonnes of CO_2 emission per every tonne of ammonia synthesized, earning the nickname of "grey ammonia". Driven by the increasing demand for food and fiber, the global ammonia production has reached around 176 million tonnes, contributing to 1.8% of global CO_2 emission (5). Consequently, the generation of waste reactive nitrogen (Nr) has surged by approximately 70% over the past three decades (6).

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In contrast, “green ammonia" is produced without relying on fossil fuels or their associated heavy CO_2 emissions, and it is expected to experience significant production growth in place of “grey ammonia”, with the potential for expanded applications (1,7,8). To produce green ammonia, green hydrogen is often obtained through water electrolysis, where water is decomposed into hydrogen (H_2) and oxygen using renewable electricity, such as wind and solar (9,10). The hydrogen then combines with unreactive nitrogen gas (N_2) through the Haber-Bosch synthesis, a process under high pressure and temperature in the presence of a catalyst, to form ammonia. The product of this green hydrogen-involving process with atmospheric nitrogen is often called “first-generation” green ammonia.

An alternative method for producing green ammonia (second generation) is to convert waste reactive nitrogen back into ammonia through direct electrochemical processes powered by renewable electricity, without producing green hydrogen (11). Novel technologies in the second generation of green ammonia production, recently developed in research laboratories, show promising potential for distributed ammonia production on a smaller scale, by upcycling waste nitrogen found in natural water bodies (11–14). This innovative approach to producing green ammonia not only helps with pollution control by reducing waste nitrogen in agricultural wastewater, but also contributes to mitigating the exacerbating issue of climate change caused byCO_2 emissions (15,16).

The development and deployment of green ammonia face significant social, economic, and environmental barriers (10,17). Green ammonia powered by renewable energy usually incurs high production costs, challenging its competitiveness as a fertilizer or a fuel (10,18). Scaling up green ammonia production to commercialization also has to overcome significant technical barriers and market risks, such as land space availability, storage and maintenance, and renewable energy intermittency (17–19). To overcome these barriers, it is crucial to provide policy support on the development of green manufacturing for ammonia, especially in the early stages. The design and provision of policy support depend on a deep understanding of the social acceptance of the new product. It is important to assess whether consumers (e.g., farmers) accept ammonia produced by green manufacturing and whether they are willing to pay a price premium for the green products. A better understanding of stakeholders’ attitudes toward green ammonia helps with the formulation and implementation of new policies that could benefit green ammonia producers and users, as well as society.

Extant literature focuses primarily on the engineering and technical challenges of green ammonia production, a tailored assessment of consumer acceptance of the green ammonia has, however, been missing. A previous study in public acceptance surveyed residents in Mexico and the U.K. regarding their attitudes toward green ammonia. The study found people in the two countries are highly supportive (20), however, this assessment of public acceptance cannot be used for estimating the approval from farmers who directly use ammonia. This is because the “not-in-my-backyard” (NIMBY) effect may exist, lowering the likelihood of farmers in adopting new products (21,22). In addition, farmers’ attitudes toward renewable energy and climate change have shown different patterns from the public (23–27).

To improve the understanding of customer acceptance, this study surveyed Iowan farmers’ attitudes towards sustainable products from green manufacturing, including ammonia (as a fertilizer or a fuel source) and hydrogen. It also collected information on farmers’ use of different nitrogen fertilizers and their attitude toward renewable energy in general.

2. Theories and Models for Technology Acceptance

Previous studies attempted to examine and explain the acceptance and adoption of new energy technologies using a variety of theories and models, many of which can be readily used to understand the customer acceptance of green ammonia. The Technology Adoption Model (TAM) is one of the most widely used models that explain the adoption of new technologies using cognitive factors. TAM presumes that behavioral beliefs about the attributes of the technology itself – perceived usefulness and perceived ease of use – are the primary determinants of an individual's attitude toward a new technology (28). Other technology attributes are also considered determinants of attitudes in studies extending the TAM model, such as perceived cost, perceived risks, and perceived controls. (29,30)

In addition to the perception of technology attributes, studies found socioeconomic, affective, and psychological factors also influence an individual's attitude toward technology adoption. Social psychological theories and models have been proposed and tested to explain pro-environmental behaviors. The Theory of Planned Behavior (TPB) predicts technology adoption intention using gain motives, that is, based on an evaluation of the outcomes (costs, benefits, and risks) of the behavior (31,32). Studies using the TPB also consider the perceived social pressure of the behavior (subjective norms) and the perceived behavioral control (ease or difficulty of performing the behavior) for determining the intention to adopt (31–34). The theory has been widely used in explaining pro-environmental behaviors, such as recycling (35), environmental and energy conservation (33,36,37), and the adoption of renewable energy and green products (34,38). The theory is convenient to practice by using the three key constructs with real-world cases, but its explanatory capability is also limited to cost-benefit calculations (39).

The Value-Belief-Norm (VBN) theory relies on normative motivations to explain pro-environmental behavior, that is, feelings of obligation to perform a behavior (40–42). Incorporating the constructs of moral drivers from the norm activation theory (43,44), the VBN model postulates that the awareness of consequences determines the ascription of responsibility, which activates personal norms for pro-environmental behavior. The VBN theory has been applied to a wide set of pro-environmental behaviors, such as natural preservation (45,46), the adoption of eco-friendly innovations (47), and willingness to pay for green electricity (48). For pro-environmental behaviors driven by self-interest, empirical studies showed a weaker prediction power for the VBN theory than for the TPB (49,50). Whereas the VBN theory was found stronger than the TPB in explaining altruistic behavior like climate change mitigation (50).

The theories and models help provide a framework for empirical testing to better understand the influential factors that could affect public support for the new technologies for green ammonia. Incorporating the important factors from the abovementioned theories and models, Huijts, Molin, and Steg proposed a "Sustainable Energy Technology Acceptance" (SETA) framework to account for the grain, normative, and heuristic motivations of technology adoption (51). Some of the important factors other than demographics are summarized here.

Perceived usefulness and ease of use. Perceived usefulness is the assessment of the technology's capability in performing the required task(s), while perceived ease of use measures the individual's evaluation of the ease or difficulty of using the new technology. Previous studies found that perceived usefulness and ease of use positively correlated with the uptake of internet-based technologies (52,53), the adoption of smart meters (30), and the acceptance of demand response (29,54).

Perceived benefits and costs. Empirical studies found high support for environmental and climate policies if people perceive benefits for the environment (55,56). Conversely, public support for environmental and climate policies will decline when significant costs are perceived (57). Many studies found the cost as a significant market barrier to the adoption of clean energy technologies (58,59). The VBN theory argues that the ascription of consequences is an important determinant of behavior intention (42).

Social norms. According to the TPB, the subjective injunctive norm is perceived expectation by important referents, which is what their parents, close friends, and other important relevant people think they ought to do. Subjective descriptive norm is perceived behavior by important referents, which is what other people do. The TPB postulates that positive subjective norms lead to higher behavioral intention (60).

Trust. Dietz, Dan, and Shwom (61) found that trust in environmentalists explains support for pro-environmental policies, while trust in industry does the opposite. Trust in professional actors, excluding the fossil fuel industry, was found critical in attitude toward adopting clean energy technology (62).

Knowledge, experience, and affect. Knowledge about renewable energy is an important factor influencing people's willingness to pay (63). A caveat is that accurate information needs to be provided to positively influence behavior intention (31). When there is a lack of knowledge and obtaining information is costly, people rely on heuristics and past experiences to make decisions. Negative emotions may strongly discourage pro-environmental behaviors or actions (64).

Worldview and religiosity. Evidence regarding religious beliefs varied as many studies found that worldview and religiosity are weak predictors for environmental attitudes. Yet church attendance is found relevant to pro-environmental behavior (65). Schultz and colleagues (66) found biblical literalism is related to more concern over environmental impacts on human, but less concern over the impacts on the ecosystem. The research found that American evangelicals are less prone to accepting the facts regarding climate change, yet their worldviews strongly forecast their endorsement of climate and energy policies (67).

Political orientation. U.S. studies found Democrats and liberals are more likely to support environmental regulations and policies (68–70). However, political orientation influences support for environmental policy "only indirectly via worldviews and environmental beliefs" (61).

None of the factors, theories, or models has been tested in extant literature to understand the social acceptance of green manufacturing for ammonia or hydrogen. Using factors identified in the SETA framework, this study attempts to assess the support of green ammonia by crop growers and estimate how their attitude is affected by socio-economic, and psychological factors.

3. Data and Method

3.1 Survey design

The survey was developed based on a literature review on green ammonia. A short description (shown below) was provided at the beginning of the questionnaire to explain the concept, production, and benefits of green ammonia. A simple diagram (Fig 1) was included along with the descriptive paragraph. Before reading this description, respondents were asked whether they were familiar with the concept and technologies used for producing green ammonia. Only about 10% of the respondents were familiar (somewhat or very). After reading the description, respondents were asked a set of questions, including attitude toward using green ammonia as a fertilizer or fuel, concerns about using green ammonia, attitude toward renewables, attitude toward an alternative valuable product – hydrogen, and a few questions about their values, beliefs, trust, and social norm, followed by questions on demographic information.

"*Scientists are developing a new method that can make "green ammonia." It's made by recycling nitrogen from water on farms and in wastewater. This process will use renewable energy from wind and sunlight. Green ammonia is not only used as a fertilizer, but also as a fuel to power machines and vehicles. This new way of making ammonia can happen right where it's needed. It can also help use less fossil fuel, prevent water pollution, and reduce greenhouse gases*."\

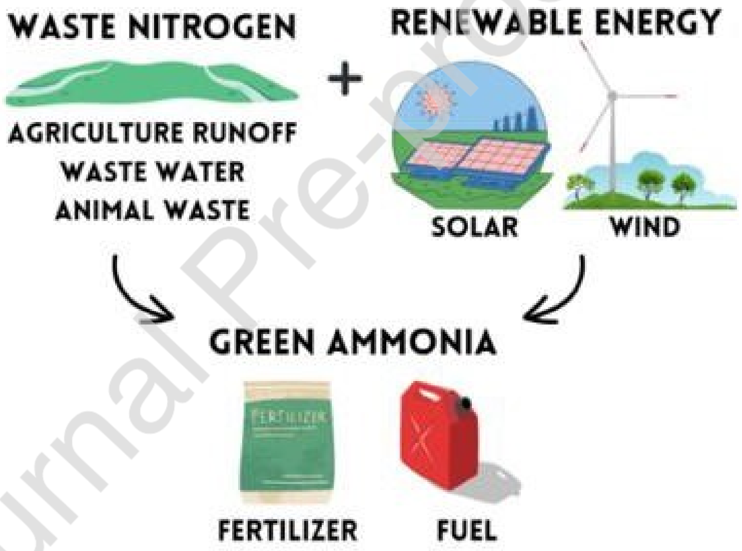


Fig 1. Infographic for Green Ammonia Survey

3.2 Survey administration

A random collection of 400 Iowa farmers (primarily crop growers) was purchased as our study sample for this mail survey study. The Iowa State University's Center for Survey Statistics & Methodology-Survey Research Services (CSSM-SRS) administrated the survey by mail. Cover letters in the first survey mailing explained the purpose of the study, requested the farmers' participation, and assured complete confidentiality of all information provided. The CSSM toll-free phone number was included so that sampled farmers could call to ask questions or express concerns about the project.

Starting on June 2023, we mailed the farmers with the cover letter, first mail survey, a reminder postcard, and a second survey to non-respondents. A total of 90 mail surveys were received from June 26 through August 8. Out of the 400 farmers, two were removed as being duplicates. A total of 21 received surveys were classified as “Not Eligible” for blank surveys or unqualified surveys returned with notes or phone calls. Cases with survey packets marked “deceased” were also classified as ineligible. This resulted in an eligible sample of 377 farmers. There were 8 cases in which postcards or survey packets were returned to CSSM by USPS marked as “unable to forward.” Because it was not known whether those cases were still involved in farming, they were retained in the eligible sample. Refusals were received from 2 people. No response was received from 282 of the sampled farmers. The response rate for this study was 24%, calculated as a ratio of completed surveys to eligible sample.

3.3 Sample data

This received sample of 90 responses includes 45 crop growers, 1 livestock grower, and 38 producers for both crops and livestock. Among them, 54% own their land, 6% rent their land, and 39% both own and rent farmland. Of the collected 90 respondents, 91% are male, 99% are white, with an average age of 65, and an average household income of $102,760. About 35% of them have a high school degree (highest diploma), while 56% have some college or college degree or higher. About 65% are working full-time or part-time, and the rest has retired. On average, the received sample of farmers is moderately religious and conservative. Table 1 presents the summary statistics of the respondents.

Table 1. Descriptive Statistics of Survey Respondents

Variable	Obs	Mean	Std. dev.	Min	Max
age	88	65	13.0358	25	91
female	87	0.1	0.2906	0	1
income ($10k)	77	10.28	5.04	1.25	17.50
religiosity	79	3.1	0.7569	1(Not religious)	4(Very religious)
ideology	81	3.7	0.8920	1(Very liberal)	5(Very conservative)
race	White: 99%; Others: 1%				
education	Some high school or less: 2% High school or GED: 35% Some college: 17% Associates or Technical degree: 21% Bachelor’s degree: 17% Graduate or Professional degree: 7%				
employment	Working full-time: 55% Working part-time: 10% Retired: 35%				

3.4 Models and variables

Ordinal logistic regression models were used to analyze the social and psychological factors affecting acceptance. The dependent variables were farmers’ acceptance of using green ammonia as a fertilizer or a fuel. Independent variables used in the acceptance models include perceived cost, perceived risk, perceived benefit, experience of using ammonia, familiarity with technology, trust, and social norm. Measurement of the variables was on a 5-point Likert scale (Table 2).

Table 2. Questions for Variable Measurement

Variable	Question
perceived usefulness	Green ammonia works just like ammonia made in the usual way.
perceived cost	Green ammonia is more expensive.
perceived benefit	Waste nitrogen could be reused instead of polluting soil and water.
perceived risk	What concerns do you have with green ammonia? _ Safety issues
experience	What are the two kinds of nitrogen fertilizers you primarily use on your cropland?
familiarity	How familiar are you with "green ammonia"?
trust	I trust scientists and engineers to develop technologies to produce green ammonia.
social norm	People around you (friends, family, neighbors) support decarbonization

4. Results & Discussion

4.1 Attitude toward green ammonia as a fertilizer or a fuel

This study directly targeted crop growers who were potential customers and producers of green ammonia. We found crop growers in Iowa have a relatively high level of support for green ammonia, while many respondents were unsure (Fig 2). About 50% of the surveyed farmers supported (somewhat or strongly) using green ammonia as a fertilizer, while only 2% opposed it (somewhat or strongly), and the remaining 47% were unsure. Support for using green ammonia as a fuel was lower – 32%, with more people unsure (57%) or opposed to it (10%). Compared with green ammonia fertilizer, about 10% more farmers are "unsure" of using it as a fuel. This high level of unfamiliarity made it a less popular idea of ammonia fuel. In addition, there was no significant difference in green ammonia acceptance among low-income farmers compared with medium- and high- income farmers (one-way ANOVA, $F(2, 73) = 1.11$, $p = 0.3336$ for fertilizer, and $F(2, 73) = 1.04$, $p = 0.3581$ for fuel). Respondents who identified as liberals showed significantly higher support than moderates and conservatives on green ammonia as a fertilizer (one-way ANOVA, $F(2, 77) = 6.39$, $p = 0.0027$) or a fuel (one-way ANOVA, $F(2, 77) = 2.39$, $p = 0.0294$).

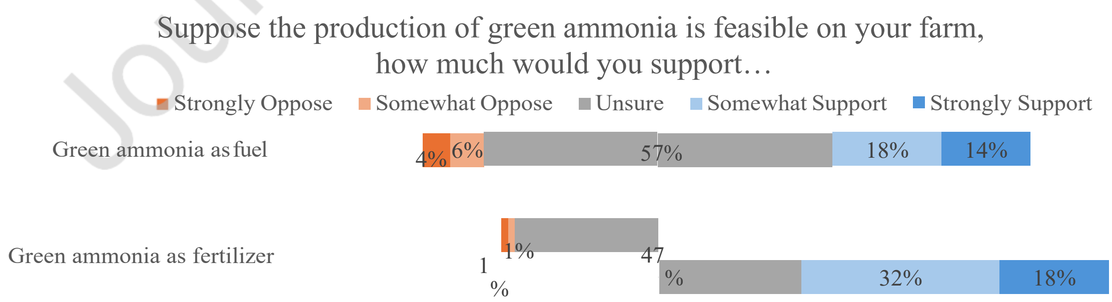


Fig 2. Crop Growers' Acceptance of Green Ammonia as a Fertilizer or a Fuel

4.2 Perceived benefits and risks

Many respondents agreed with the benefits of recycling waste nitrogen, while their opinion on the technical and economic risks of green ammonia varied. About 53% of respondents agreed (somewhat or strongly) with the statement that "waste nitrogen could be reused instead of polluting soil and water," while only 2% disagreed and 42% were unsure. Most farmers were unsure about the risks that "green ammonia is more expensive" (86%) and "green ammonia works just like ammonia made in the usual way" (77%). There was no statistically significant difference in the perceived benefits and risks between liberals and conservatives.

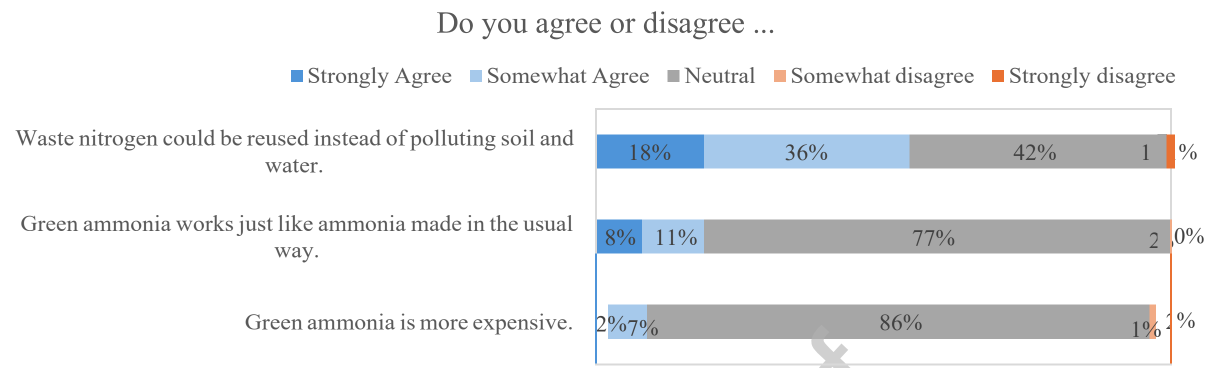


Fig 3. Perceived Benefits and Risks with Green Ammonia

4.3 Concerns about green ammonia

Many farmers were asked to express concerns over the production specifics of green ammonia, including maintenance, storage, to land use. The top concerns (moderate and great) were maintenance of the production system (48%) and storage (46%). There are also relatively high concerns about safety (41%), on-site production (39%), and land use (31%). Concerns about using renewables as power sources and recycling waste nitrogen are the lowest. There is no statistically significant difference in the concerns between liberals and conservatives.

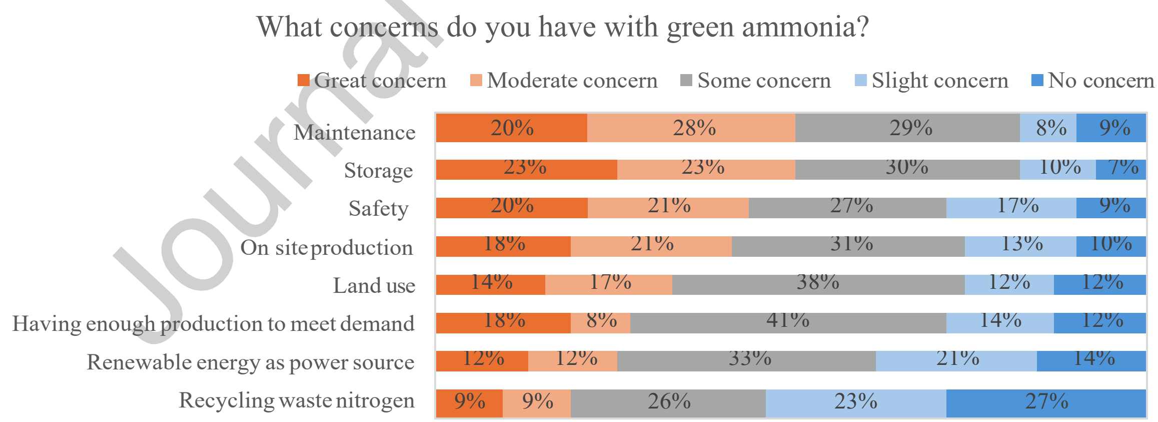


Fig 4. Concerns about Green Ammonia Production and Usage

4.4 Support of renewable energy

Regarding the use of renewable energy, two approaches were tested: purchasing electricity produced from renewables or directly installing renewable energy systems on their farmland. We found wide differences between the two approaches. There was a high level of support (somewhat or strongly) for using green electricity produced from solar (79%) and wind (63%) and a low level of opposition (9% for solar and 20% for wind). On the other hand, support for installing solar panels on respondents' farmland was 55%, with 24% opposition. Support for installing wind turbines on respondents' farmland was 26%, with more opposition (48%). This contrast in support suggests a significant barrier from the NIMBY effect (71,72) to the on-site production of green ammonia using on-site wind electricity. In comparison with on-site wind energy, the NIMBY syndrome was not an influential factor for on-site solar energy, as there was no large difference in the support levels of electricity produced from solar versus installing solar directly. In general, liberals showed the highest level of support for renewables, and conservatives had a lower level of support than liberals and moderates.

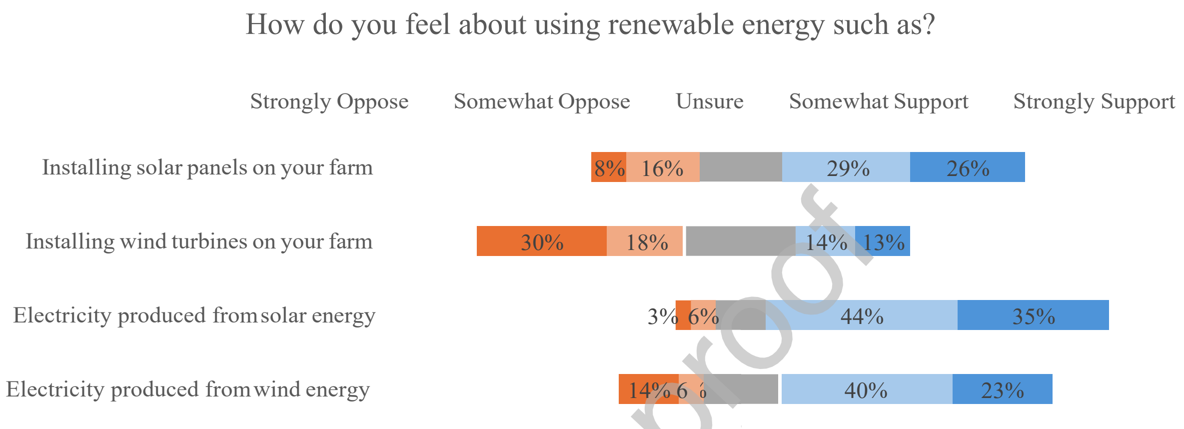


Fig 5. Crop Growers' Acceptance of Renewable Energy

4.5 Attitude towards Hydrogen

There was a higher percentage of respondents (24%) who opposed to producing hydrogen on their farmland than those (17%) in support of it. Interestingly, the number of respondents in support of and in opposition to using hydrogen on their farms was the same (20%). Attitudes toward the use and production of hydrogen were quite negative compared with the attitude toward renewables and green ammonia. The lack of support for hydrogen reveals a significant barrier for the first-generation green ammonia, which still uses green hydrogen (from water electrolysis) as an intermediate agent through the Haber-Bosch process. This finding implies a strong preference for the second-generation green ammonia (direct electroreduction of reactive waste nitrogen) over the first-generation technologies that use hydrogen.

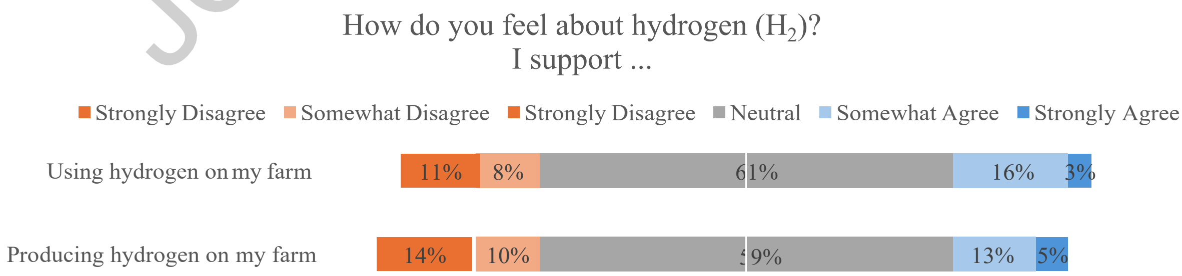


Fig 6. Crop Growers' Acceptance of Hydrogen Production and Usage

Meanwhile, the majority of respondents (59%–61%) conveyed a high level of uncertainty regarding hydrogen. The most respondents (66%–71%) were unsure about the potential benefits and risks. About 23% agreed that hydrogen poses “high safety risks”, while 16% thought “hydrogen is expensive”. About 23% of respondents viewed hydrogen as a clean energy source.

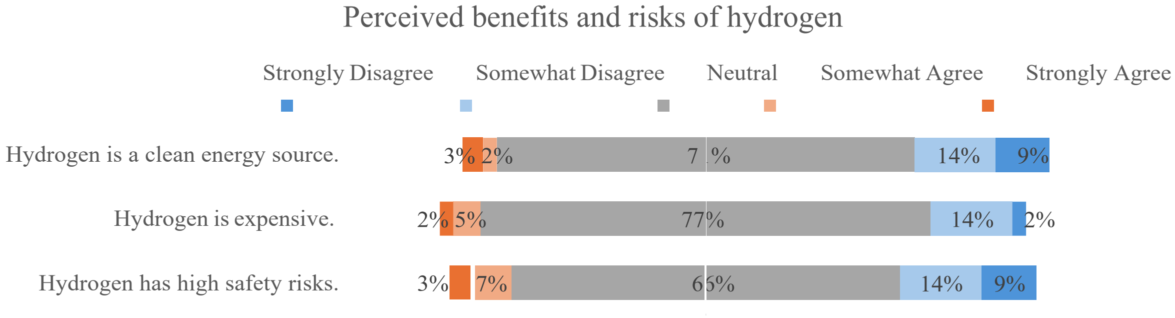


Fig 7. Perceived Benefit, Risk, and Cost of Hydrogen

The survey results also showed a slightly higher acceptance of using hydrogen fuel cells to power vehicles. The estimated support level for hydrogen fuel cells used in passenger cars was 36%, with 16% opposition. For using hydrogen fuel cells in trucks, 26% of farmers supported the use, with 22% opposition. For using hydrogen fuel cells to power farming machinery, the support level was only 20%, with 31% opposed. The acceptance level was the same (20%) for both using hydrogen fuel cell-powered machinery and using hydrogen on-site.

4.6 Fertilizer use

About 48% of the surveyed crop growers in Iowa primarily used a specific type of ammonia as nitrogen fertilizer, such as anhydrous ammonia, ammonium sulfate, ammonium nitrate, or aqua ammonia. Another 26% primarily used urea, and 21% mainly used nitrogen solutions (i.e., urea-ammonium-nitrate, UAN solutions). The observed heavy application of ammonia and its derivatives strongly suggests a great market potential for green ammonia to be adopted by farmers as a nitrogen fertilizer.

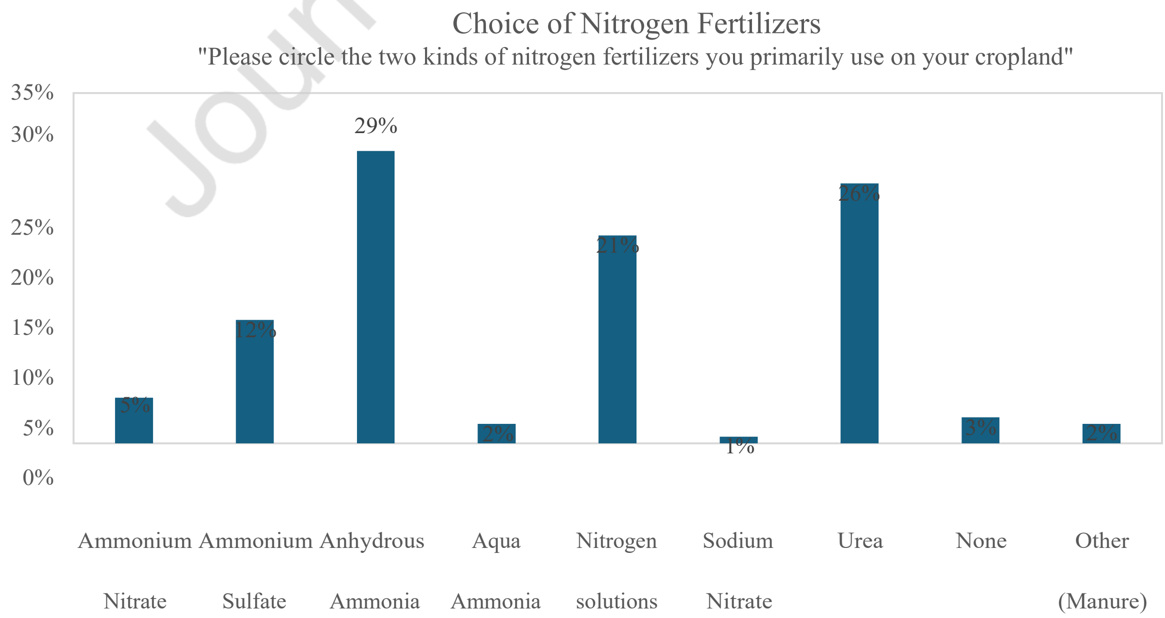


Fig 8. Crop Growers’ Choices of Nitrogen Fertilizer

4.7 Factors influencing green ammonia acceptance

Factors influencing crop growers' support for green ammonia as a fertilizer were examined using ordinal logistic regression analysis. Validity tests were conducted on the key assumption for ordinal logistic regressions – proportional odds, also called the parallel regression assumption. The likelihood ratio chi-squared (χ^2) = 6.691 (probability, P > χ^2 = 0.979) was consistent with the Wald test (χ^2 = 4.897, P > χ^2 = 0.996) and the Wolfe Gould test (χ^2 = 5.942, P > χ^2 = 0.989), suggesting that the parallel regression assumption was not violated. This indicated that the ordinal logistic regression analysis was an appropriate model for analyzing the data on green ammonia as a fertilizer. However, the ordinal logistic regression did not show a good fit for green ammonia as a fuel (likelihood ratio χ^2 = 62.48, P > χ^2 = 0.000), because many of the independent variables (see Table 2) were not suited for ammonia fuel.

Table 3 presents the estimated effect on acceptance of green ammonia as a fertilizer for the independent variables, measured in coefficient (b), odds (e^b), and percentage change in odds (%). Although ordinal logistic regression didn't fit a good model for analyzing the support for ammonia fuel, the model result is also presented in Table 3 for comparison purposes only (coefficients are not interpreted). Model results exhibited that crop growers' acceptance of green ammonia fertilizer was largely affected by the perceived benefit, experience of using ammonia, trust in scientists and engineers for developing the green ammonia technologies, social norms that people around them support decarbonization, gender, income, and ideology.

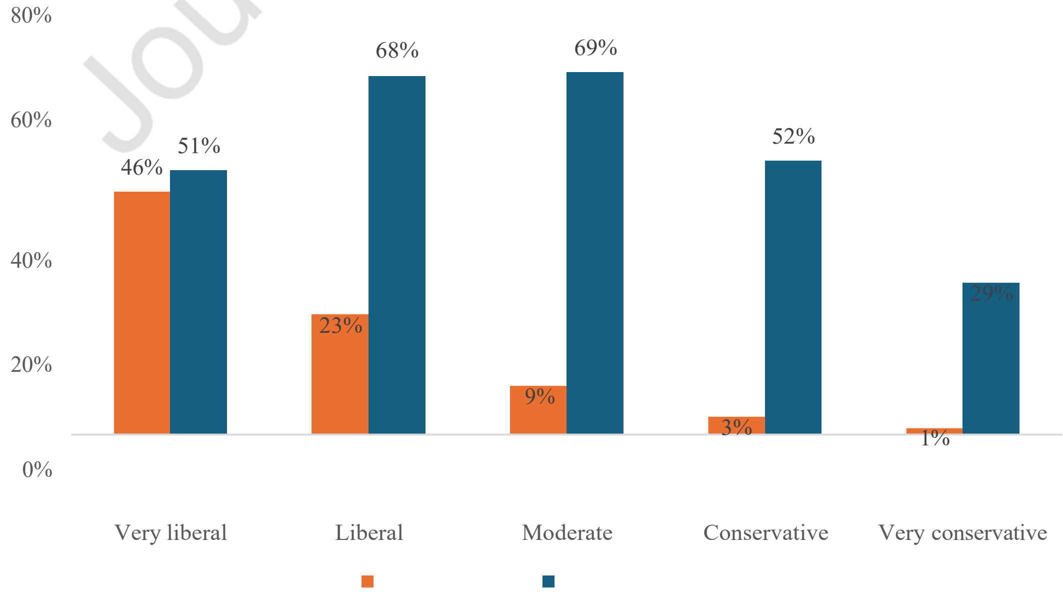
Table 3. Ordinal Logistic Regression Analysis of Support for Green Ammonia as a Fertilizer or a Fuel

	(1) fertilizer			(2) fuel		
	b (std. err.)	e^b	%	b (std. err.)	e^b	%
perceived usefulness	-.1447 (.6575)	0.865	-13.5	-.5525 (.5281)	0.576	-42.4
perceived cost	.3825 (.6152)	1.466	46.6	.1667 (.5661)	1.181	18.1
perceived benefit	1.7088*** (.5485)	5.522	452.2	.779* (.4387)	2.179	117.9
perceived risk	.2966 (.2815)	1.345	34.5	.0694 (.2543)	1.072	7.2
Ammonia use	1.1381* (.6331)	3.121	212.1	.2852 (.5432)	1.33	33
familiarity	-.8085 (.5119)	0.446	-55.4	.101 (.4207)	1.106	10.6
trust	1.7711*** (.5143)	5.877	487.7	1.4201*** (.4309)	4.138	313.8
social norm	1.0797** (.4681)	2.944	194.4	.2698 (.3747)	1.31	31
age	-.0487 (.0308)	0.952	-4.8	-.0394 (.0241)	0.961	-3.9
education						
some college	.8494 (1.0726)	2.338	133.8	.4212 (.9003)	1.524	52.4
associates	-1.352 (.9484)	0.259	-74.1	-.2658 (.8339)	0.767	-23.3
bachelors	-.8902 (.8301)	0.411	-58.9	.0575 (.7715)	1.059	5.9
graduate	-.4397 (1.7211)	0.644	-35.6	1.0005 (1.2986)	2.72	172

income	.1563**	1.169	16.9	.0415	1.042	4.2
	(.0645)			(.0549)		
religiosity	.6959	2.006	100.6	.1632	1.177	17.7
	(.5257)			(.421)		
ideology	-1.2672***	0.282	-71.8	-.4936	0.61	-39
	(.4753)			(.3506)		
/cut1	3.3511			-1.4089		
	(4.6431)			(3.5146)		
/cut2	12.5022***			1.6724		
	(4.8448)			(3.4178)		
/cut3	15.8099***			5.7459*		
	(5.0308)			(3.4497)		
/cut4				7.3018**		
				(3.5035)		
Observations	70			70		
Pseudo R^2	.4305			.2178		

Standard errors are in parentheses
**** p<.01, ** p<.05, * p<.1*

More specifically, for every one-unit increase (on a 5-point Likert scale) in perceived benefit (e.g., increase from "unsure" to "somewhat agree" with perceived benefit in reducing waste nitrogen), the odds for supporting green ammonia as a fertilizer would increase by 452%, when holding other variables constant. Similarly, for every one-point increase in trust, the odds of supporting green ammonia would increase by 488%; for every unit increase in social norm, the odds would increase by 194%. For crop growers who primarily use ammonia as a nitrogen fertilizer, the odds for them to accept green ammonia would be 212% higher than crop growers who don't use ammonia. Moreover, higher-income and more liberal-leaning farmers would have a higher tendency to accept green ammonia as a nitrogen fertilizer. Higher-income farmers would have a higher level of support; the odds for crop growers to accept green ammonia would increase 17% for every $10,000 increase in income. Whereas conservatives would be less supportive than moderates and liberals (Fig 7). The estimated support (somewhat and strong) by the very liberal (97%) and liberal (91%) farmers would be much higher than the conservatives (56%) and very conservatives (30%), when holding other variables at their means.



strong support somewhat support

Fig 9. Estimated Marginal Probability of Support by Ideology

5 Conclusions

A random collection of Iowan farmers (99% crop growers) was studied regarding their attitudes toward green ammonia produced by upcycling waste nitrogen and using renewable energy. About 50% of the surveyed farmers supported using green ammonia as a fertilizer, with only 2% in opposition. Support for using green ammonia as a fuel was lower – 32%, and 10% opposed. At the same time, about 48% of the surveyed crop growers in Iowa mainly used a certain type of ammonia as their nitrogen fertilizer, indicating significant market potential for green ammonia.

Most surveyed farmers were unfamiliar with green ammonia before reading the description in the survey. Many of them were unsure about the function and price of green ammonia - 86% were unsure about "green ammonia is more expensive", and 77% were unsure whether "green ammonia works just like ammonia made in the usual way". But there was a higher level of agreement on recycling waste nitrogen (53%) to make green ammonia, compared to the low support for producing hydrogen (17%). This finding indicates a strong preference for the second-generation technology over the first-generation green ammonia produced using electrolysis hydrogen. In addition, many farmers were concerned about the maintenance, storage, safety, on-site production, and land use for green ammonia production.

This study also observed a high level of acceptance of using green electricity (but not directly installing wind or solar on their farmland), and a relatively high level of uncertainty with the use of hydrogen. Ordinal logistic regression analysis identified a set of socioeconomic and psychological factors affecting the attitude toward green ammonia, including income, ideology, perceived benefit of recycling waste nitrogen, experience with using ammonia, trust in scientists and engineers to develop green ammonia technologies, and social norms related to support of decarbonization. More specifically, for every one-unit increase (on a 5-point Likert scale) in perceived benefit (e.g., increase from "unsure" to "somewhat agree" with perceived benefit in reducing waste nitrogen), the odds for supporting green ammonia as a fertilizer would increase by 452%, when holding other variables constant. Similarly, for every one-point increase in trust, the odds of supporting green ammonia would increase by 488%; for every unit increase in social norm, the odds would increase by 194%.

Findings from this study provide significant policy implications in support of green ammonia technology development. First, policy support could focus on the following technologies with high acceptance: (1) the 2nd generation technologies without the involvement of hydrogen, (2) technologies that produce environmental benefits, such as reducing waste nitrogen, (3) decentralized systems with on-site solar power generation, and (4) large-scale production systems with wind power. Secondly, the government could consider providing financial incentives to green ammonia, such as tax benefits for production and discounted prices. Thirdly, outreach and community engagement programs should be devoted to communicating with farmers about the new technologies. Regular and effective communication helps build a trustworthy relationship with crop growers, while making green ammonia more familiar. These programs could design engagement and communication materials that better target conservative groups.

Nevertheless, this study is based on data collected from Iowan crop growers, which face limitations in generalizing the findings. Results of this study could represent farmers in the Midwest because the Midwest rural population is relatively homogenous in demographics and culture (73). Generalization to other regions is not recommended due to social and climate differences. More research with broader coverage is needed to provide a better understanding of farmers' attitude toward green ammonia.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: