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What are stakeholder views and needs for achieving phosphorus sustainability?

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Abstract

Our society depends on the effective management of phosphorus (P). Phosphorus is a key component of agricultural fertilizers to improve crop yields, and also plays a critical role in many industrial processes and consumer products. In the past decade, there have been numerous calls for innovative approaches to manage P more sustainably, as it is a nonrenewable resource that can adversely impact aquatic ecosystems from runoff and inefficiencies in P use. To develop more sustainable solutions that will ultimately be adopted, diverse stakeholder perspectives must be recognized, including those in industry, government, academia, non-governmental organizations, and other civil groups. This study responds to this need by identifying stakeholder views, needs, concerns, and challenges regarding P sustainability. An online survey was developed and deployed to individuals identified as P sustainability experts and professionals in the U.S. and abroad. Based on responses from 96 stakeholder participants from a range of sectors, areas of expertise, and geographies, we found that the vast majority of stakeholders considered current P use to be unsustainable and were very concerned about the ability to manage P sustainably. Stakeholder participants did not distinguish between urgent and long-term challenges, and perceived financial and regulatory issues to be of greatest importance. Stakeholder participants expressed a range of needs to improve P management systems, including improved management practices, new technologies, enhanced regulations, and better approaches for engagement. Outcomes from this work can help inform future research, engagement, and policy priorities to ensure sustainable P management solutions based on stakeholder-identified perspectives and needs.

Keywords Phosphorus sustainability · Stakeholders · Perceptions · Challenges

1 Introduction

Over the past decade, there have been numerous calls from researchers and scholars to develop innovative approaches to sustainably manage phosphorus (P) (Cordell and White 2013; Scholz et al. 2014; Jacobs et al. 2017; Brownlie et al. 2022). This is because our society is heavily dependent on P, primarily through its use in agricultural fertilizers where it drives global food production, and it also plays a critical role in many industrial processes and consumer products. At the same time, there are a number of inefficiencies in its use and management that threaten its long-term sustainability and contribute to degraded ecological systems (Schröder et al. 2011; Scholz et al. 2014). For example, excessive fertilizer use in agriculture has resulted in legacy P in soils, and resulting runoff can lead to eutrophication, harmful algal blooms, and marine dead zones (Nedelciu et al. 2020; Missimer et al. 2020; Cerven et al. 2021). Further, P is currently mined from nonrenewable phosphate rock that is available in only a few locations worldwide (Filippelli 2011). In response to these challenges, various research initiatives have been put forward to more efficiently use P in agricultural production, capture P in water and wastewaters, and generally improve the circularity of the P-economy across various sectors (Rittmann et al. 2011; Cordell and White 2011; Kümmerer et al. 2020) For example, the Our Phosphorus Futures project recently identified 10 key areas for research,

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including those to reduce P-inputs within agricultural contexts, reduce P-losses to the environment, and improve P recovery and recycling (Brownlie et al. 2022).

Alongside research efforts to advance P sustainability have been calls for improved stakeholder engagement and cooperation (Lyon et al. 2020; Brownlie et al. 2022; Martin-Ortega et al. 2022; Deviney et al. 2023). In the case of P sustainability, key stakeholder groups include industry (e.g., agriculture, mining, fertilizer industries), government (e.g., policy-makers), academia (e.g., researchers), non-governmental organizations (NGOs) (e.g., environmental groups), and other civil groups (e.g., consumer advocacy groups). Engaging stakeholders can help ensure solutions meet their needs while improving the potential for adoption and diffusion across sectors. Further, engaging these actors in decision-making also aligns with principles of responsible innovation, through integrating diverse perspectives and responding to these needs in research and innovation design (Stilgoe et al. 2013; Grieger et al. 2022a, b). While the integration of perspectives and needs has widely been considered to be an essential component of developing effective P management solutions (Cordell 2008; Metson et al. 2015; Jacobs et al. 2017), there are comparatively few published studies that report stakeholder perspectives and needs within P-specific contexts (Deviney et al. 2023). In other words, while there are numerous calls for strengthening engagement to improve the sustainable management of P, there has been very little research that has investigated how these stakeholder perceive the issue of P sustainability and what challenges they experience to achieving P sustainability.

This study aims to overcome this gap by eliciting the views of diverse stakeholders in terms of their perceptions and needs regarding P sustainability. To achieve the goals of the study, we developed and deployed an online survey among researchers, professionals, and other experts working in fields of food and agriculture, nutrient management, water resources, and sustainability sectors in the U.S. and abroad. Overall, results from this study may help inform future research, engagement, and policy priorities to ensure sustainable P management solutions based on stakeholder-identified perspectives and needs.

2 Methods

2.1 Participant identification and outreach

The goal of this study was to survey experts and professionals working in diverse fields of P sustainability regarding their perceptions and needs related to P sustainability. To identify potential study participants, we pursued several different strategies. Specifically, we consulted peer-reviewed literature, conference and seminar programs and speaker lists, as well as the research team's networks focused on food and agriculture, nutrient management, water resources, and P sustainability sectors in the U.S. and abroad. We also sent announcements to mailing lists of relevant organizations and groups that included the Sustainable Phosphorus Alliance and the Water Research Foundation. In total, we invited approximately 1100 potential participants to participate in the online survey via email. In addition to reaching out to study participants via email, the link to the online survey was also distributed to its members through social media hosted by Sustainable Phosphorus Alliance (i.e., LinkedIn). Participants were affiliated with a range of academic institutions, industry, non-governmental organizations (NGOs), advocacy groups, and government agencies. The outreach email included an overview of the survey, approximate time it would take to complete, potential benefits of participating, and how information and results were handled. Prior to reaching out to participants, the research team submitted the survey protocol to the PI's research institution (NC State, IRB protocol 25,268), which was deemed to be IRB exempt.

2.2 Survey development

The survey was developed with the online survey platform Qualtrics. The survey was conducted anonymously and no identifying participant information was collected. In total, there were 14 multiple-choice questions to gauge respondents' views of P sustainability, key challenges, and needs to achieve P sustainability. Within each of the 14 multiple-choice questions, participants were also able to select an "other" response option where they could provide an open-ended response if needed. An overview of these questions is included in Table 1 and a complete list of survey questions along with participant responses are included in the Supplementary Information (SI).

The survey asked respondents to indicate if they currently work in fields of P management, their level of familiarity with P sustainability, along with their sector(s), area(s) of expertise, and geographic location(s) (Q1–Q5, Table 1). Participants were then asked to provide their views of P sustainability and their level of concern (if any) (Q6–Q9) as well as short-and long-term challenges related to P sustainability (Q10, Q11). In the last section of the survey, participants were asked about their needs to achieve more sustainable P management systems (Q12–Q14).

2.3 Survey dissemination and data collection

All study participants were able to directly access the survey using a link included in the outreach emails and/or posted on social media. The survey was distributed to potential participants between September 1 and November 7, 2022. After the study period ended, the survey was closed and participants

Table 1 Survey questions posed to study participants regarding P sustainability

Category	Survey question
Respondent information	1. Do you currently work in, conduct research, and/or are involved in activities related to phosphorus management?
	2. Which of the following best describes the sector(s) you are currently affiliated with?
	3. Which of the following best describes the kind of work that you do, and/or the area of your expertise?
	4. Which of the following best describes the geographic location(s) where you work?
	5. How familiar are you with the existing system(s) to manage phosphorus?
Views and concerns	6. How sustainable are current phosphorus management systems?
	7. How concerned or unconcerned are you about the current ability to manage phosphorus sustainably?
	8. Why do you think that the current phosphorus management systems are [respondent's answer to question 6]?
	9. Why are you [respondent's answer to question 7]?
Challenges and needs to achieve P sustainability	10. What are the most urgent or pressing challenges that you or your organization currently face in managing phosphorus sustainably?
	11. What are some long-term challenges for you or your organization to manage phosphorus sustainably? These include issues that may be less pressing, but need to be addressed in the next 5–10 years
	12. What would help you or your organization achieve more sustainable phosphorus management systems?
	13. Thinking about the past few years, have you or your organization explored or considered the use of new technologies to manage phosphorus?
	14. Which of the following factors are important to you or your organization when considering or deciding on a new technology/technologies for phosphorus management?

were no longer able to access the survey. Study participants were required to provide consent before responding to survey questions.

A total of 125 participants agreed to participate in the study and completed part of the survey, which is equivalent to an 11.4% response rate. While this is lower than the typical average for online surveys (Wu et al. 2022), it is comparable to another recent study that investigated perceptions of sustainability in academic contexts (Aminpour et al. 2020). Out of the 125 initial study participants, 103 participants completed the entire survey. Using the responses from the 103 participants that completed the survey, we then reviewed and cleaned the data to remove incomplete or invalid responses. In this step, responses from seven participants were removed since (i) four participants had ReCaptcha values below 0.8 and may have been potential bots, (ii) one participant response was flagged as ballot box stuffing (i.e., an individual responded to the survey more than once), and (iii) two participants replied that they did not agree to participate and therefore their responses were removed. This resulted in a dataset consisting of valid and completed responses from 96 participants, and therefore considered to be the final sample size for this study.

Out of the 96 participants who completed the survey, more than 80% of participants reported to currently work in, conduct research, and/or are involved in P management ($n = 78$ responses) (Table S1 in SI). The greatest proportion of participants reported to be affiliated with academia, followed by industry/private sector, government/public sector, and NGO, advocacy group, and/or trade associations (Fig. 1A, Table S2 in SI). A small percentage of respondents reported being affiliated with the general public and 'other' organizations, which represented sectors of education, environmental consulting, environmental planning, and water utility (Table S2 in SI). Participants also reported their areas of expertise across various disciplines related to P management, with the greatest proportion of participants with expertise in Water quality and Agriculture-produce/crops (Fig. 1B, Table S3). In addition, participants also reported their areas of expertise within Agriculture- livestock, Soil science, Knowledge transfer/sharing, Wastewater management, Fertilizer production, Phosphorus recovery/reuse, with other areas of expertise in ecology, legal or regulatory issues, social issues, food security/food systems, biotechnology, phosphate mining/extraction, solid waste management, consumer goods, and 'other' areas (Fig. 1B, Table S3 in SI). Of the participants who selected 'other' areas of expertise, they further specified these as the following: agricultural consulting, constructed wetlands, forestry, meteorology and climate science, public health (nutrition), and public health (vector control) (Table S3).

Participants reported that they were located in the southeast U.S. ($n = 39$, 30.5%), international countries ($n = 28$, 21.9%), midwest U.S. ($n = 26$, 20.3%), northeast U.S. ($n = 19$, 14.8%), as well as southwest U.S. and west U.S. ($n = 8$, 6.3%, each) (Table S4 in SI). In addition, nearly 3/4ths (i.e., 73%) of the participants reported to be either very familiar or extremely familiar with existing system(s) to management P ($n_{\text{Very familiar}} = 55$, 57.3%; $n_{\text{Extremely familiar}} = 15$, 15.6%), while less than 20% of participants reported to be either slightly

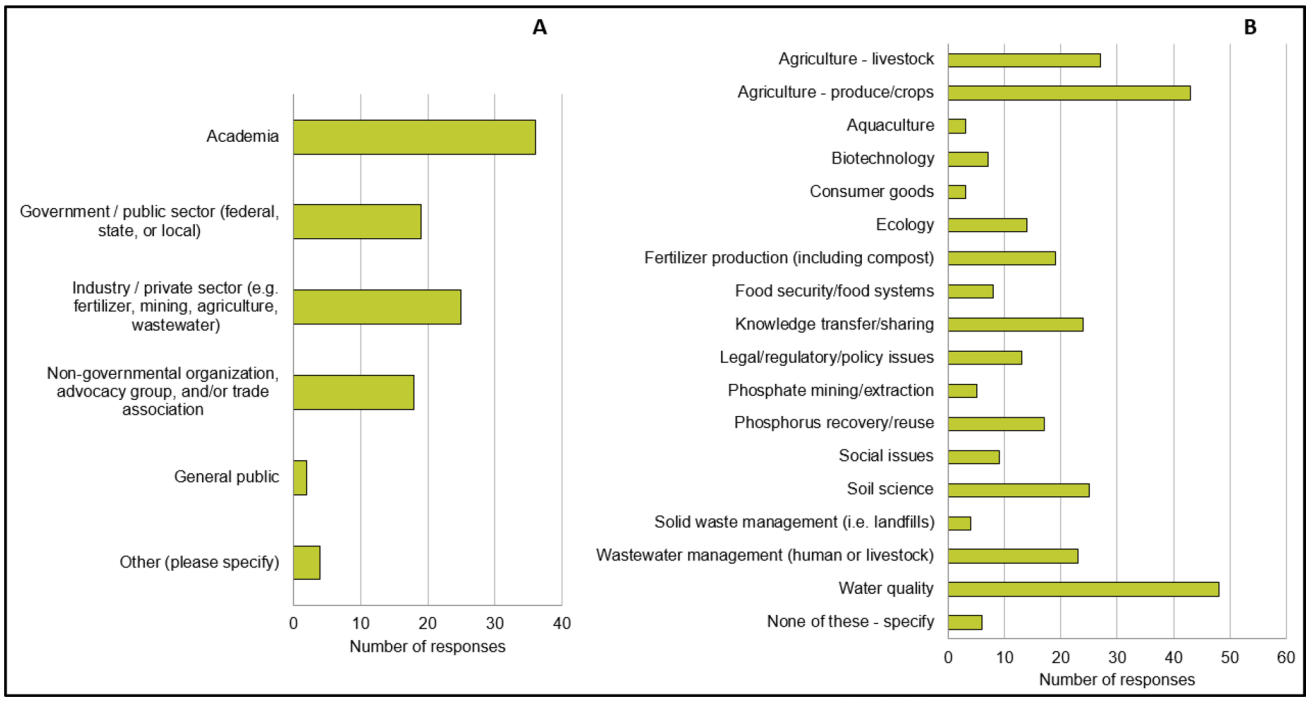

Fig. 1 Distribution of stakeholder study participants across sectors (**A**) and areas of expertise (**B**). Participant responses to **A** "Which of the following best describes the sector(s) you are currently affiliated with?" and **B** "Which of the following best describes the kind of work that you do, and/or the area of your expertise?"

familiar or not familiar at all ($n_{\text{Slightly familiar}} = 14$, 14.6%; $n_{\text{Not familiar}} = 3$, 3.1%) (Table S5 in SI).

2.4 Survey analysis

After the study was completed, responses were exported from the Qualtrics platform for qualitative analysis. For the multiple-choice questions, frequency and percentage of participant responses were calculated from the 96 participants who completed the survey using in SPSS version 28.0.0.0. Figures were also developed to illustrate the results across survey questions. To investigate if there is a relationship or correlation between categorical variables (e.g., participant views of P sustainability and reported levels of concern), Pearson Chi-square tests were run in SPSS. For the open-ended questions, qualitative software (Dedoose) was used to code participant responses using descriptive coding processes. In this step, we reviewed participant responses, identified key themes that emerged, and assigned codes and subcodes. All survey questions and results generated are located in the SI.

3 Results

3.1 Views and concerns related to P sustainability

The vast majority of survey participants responded that they considered the current P management systems to be either slightly sustainable ($n = 44$ responses, 45.8% of all responses) or not sustainable at all ($n = 29$ responses, 30.2% of all responses) (Fig. 2A; Table S6 in SI). Less than 15% of participants considered the current P management systems to be neither sustainable or unsustainable ($n = 14$, 14.6%) or very sustainable ($n = 4$, 4.2%) (Fig. 2B; Table S7 in SI). No participants described P management systems as "extremely sustainable." In addition, nearly two-thirds of survey participants reported to be very concerned about the current ability to manage P sustainably ($n = 60$, 62.5%), followed by nearly 20% who indicated they were slightly concerned ($n = 19$, 19.8%), extremely concerned ($n = 12$, 12.5%), and neither concerned or

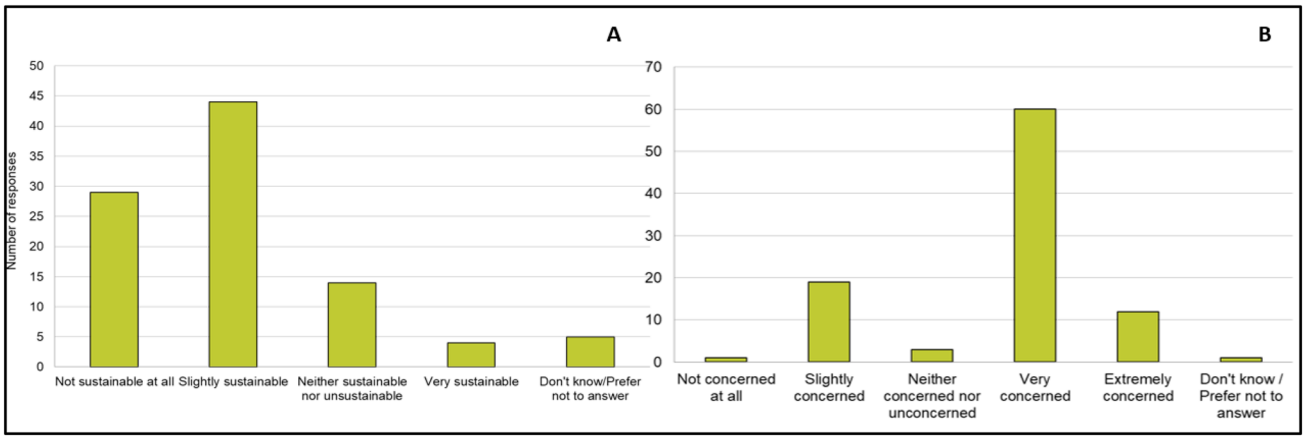

Fig. 2 Stakeholder participant views of P sustainability (**A**) and perceived level of concern (**B**). Responses to **A** "How sustainable are current phosphorus management systems?" and **B** "How concerned or unconcerned are you about the current ability to manage phosphorus sustainably?"

unconcerned ($n = 3$, 3.1%). Only one participant indicated they were not concerned at all ($n = 1$, 1%). The relationship between participant responses that reported their views of P sustainability and level of concern was investigated for association using a Pearson Chi-square test (i.e., test statistic of 63.390, 20 degrees of freedom, p value < 0.001) (Table S7 in SI). These data demonstrate a strong significant relationship between participant views of P sustainability and their reported level of concern.

When asked to elaborate on why they viewed the sustainability of P management systems sustainable/unsustainable, 85 open-ended responses were provided by participants (Table S8 in SI). The majority of responses were from those who indicated they considered P management systems to be either slightly sustainable ($n = 39$) or not sustainable at all ($n = 29$), largely due to themes related to challenges of P recovery, the use of a finite/non-renewable resource, environmental impacts, and current agricultural practices (Fig. 3A, Table S8). For instance, one participant commented that "Relying on a mined, non-renewable resource for an essential nutrient for all life, while the excess is lost to landfills and water bodies is just not sustainable" (Table S8). Thirteen responses provided by participants indicated P management systems were neither sustainable nor unsustainable due to a range of themes (e.g., agricultural practices, environmental impacts, challenges of P recovery), while four responses were received that indicated stakeholders considered P management systems to be very sustainable due to current agricultural practices and P fertilizer applications. The latter view is exemplified by a stakeholder who commented "Our P fertilizer management practices are just about as good as they can be given the current knowledge and technology available to the industry in my region" (Table S8).

When asked to elaborate on why they were concerned or unconcerned about the current ability to manage P sustainably, 89 open-ended responses were provided by participants (Table S9 in SI). The vast majority of these responses were from participants who indicated they were very concerned ($n = 56$) or extremely concerned ($n = 12$), due to themes related to environmental impacts, challenges of P recovery, the use of a finite/non-renewable resource, and current agricultural practices (Table S9, Fig. 3B). For instance, one participant commented that "P is a finite essential element for all life. It is being used in an inefficient, polluting way" (Table S9). Seventeen responses were provided by participants who indicated they were slightly concerned while three responses indicated they were neither concerned or unconcerned, all of which were related to themes largely related to current agricultural practices, policy/politics, fertilizer applications, and environmental impacts. One stakeholder response indicated they were not concerned at all about P management systems because of agricultural practices and policies, as exemplified by the comment "We already have a lot of regulations in place, and all commercial animal production farms have approved plans in place and are audited to be compliant" (Fig. 3B, Table S9).

3.2 Challenges and needs to achieve P sustainability

Across all responses from stakeholder participants, market or financial challenges ($n_{urgent} = 54$ responses, 24.4% of all responses; $n_{longterm} = 56$, 25.5%) as well as regulatory challenges ($n_{urgent} = 50$, 22.6%; $n_{longterm} = 56$, 25.5%) were the top issues participants faced to manage P sustainably in the near and long-term (Fig. 4A, Table S10). Next, participants indicated that they face technological challenges ($n_{urgent} = 33$,

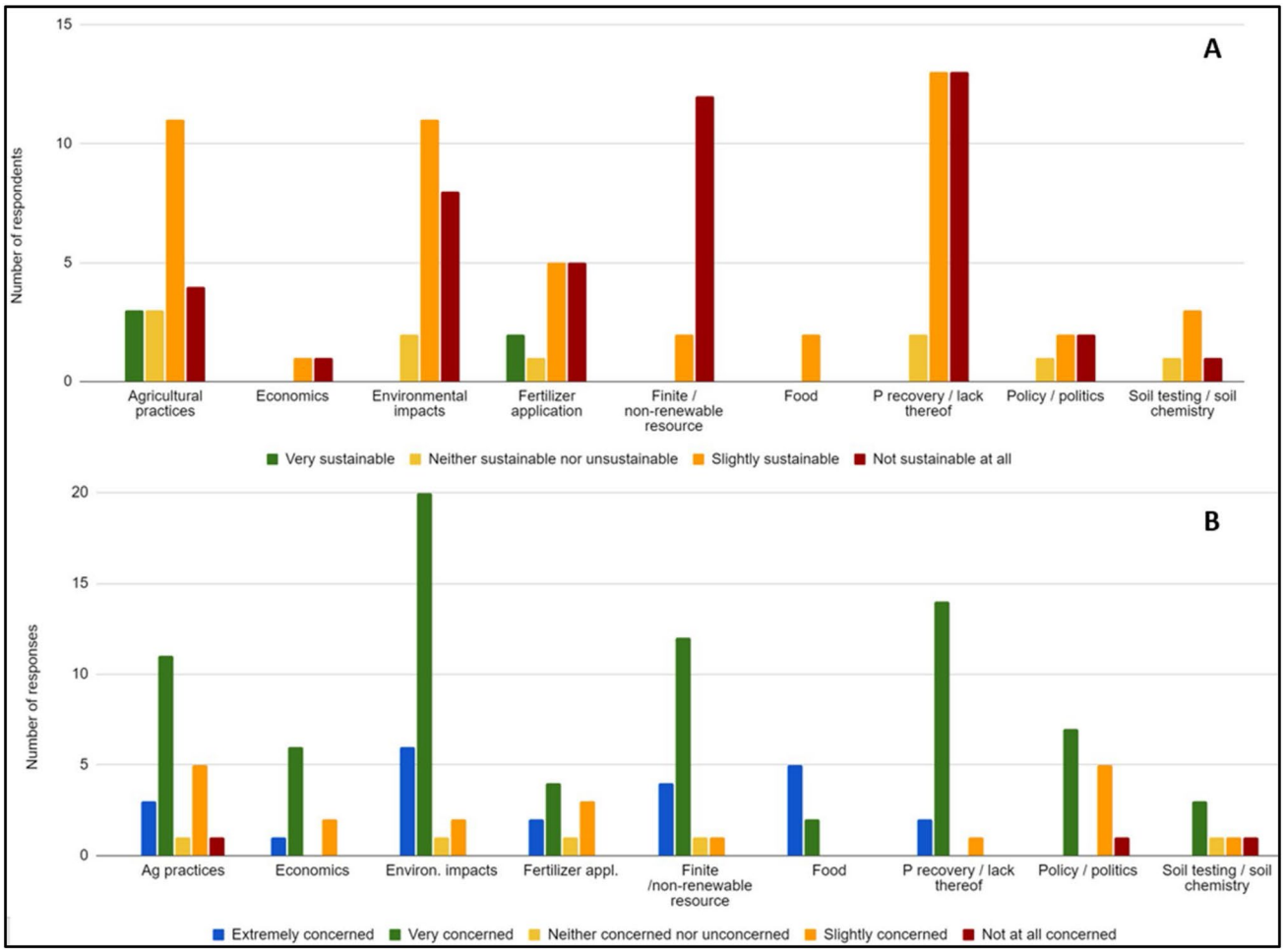

Fig. 3 Stakeholder responses to open-ended questions on why participants thought P management systems were sustainable/unsustainable (**A**) and why indicated they were concerned/unconcerned (**B**). Responses to **A** "Why do you think that the current phosphorus management systems are [respondent's answer to question no. 6; how sustainable are current P management systems]?" and **B** "Why are you [respondent's answer to question no. 7; how concerned/unconcerned are you about the current ability to manage P sustainably]"

14.9%; $n_{\text{longterm}} = 38$, 17.3%), societal and/or ethical challenges ($n_{\text{urgent}} = 36$, 16.3%; $n_{\text{longterm}} = 35$, 15.9%), as well as logistical challenges ($n_{\text{urgent}} = 25$, 11.3%; $n_{\text{longterm}} = 22$, 10.0%) (Fig. 4A, Table S10). In addition, participants identified other urgent ($n_{\text{longterm}} = 12$, 5.4%) and long term ($n_{\text{longterm}} = 5$, 2.3%) challenges, many of which fit within broad categories of, e.g., manure management, education for farmers on BMPs, or weather variability (see Table S10 for all details). Participant responses to urgent and long-term challenges are consistent (Fig. 4A), meaning that participants largely considered the same challenges to be an issue in both the near and long terms defined as "urgent" and "in the next 5–10 years" respectively.

When stakeholder responses to the challenges they face were disaggregated by sector, overall there were consistent responses across different sectors (Fig. 4B, Tables S11, S12). Only slight differences were observed, where for example academic participants reported most on the logistical challenges compared to other sectors, while government-affiliated participants reported most on technological challenges and industry reported on market/financial challenges.

When participants were asked what they or their organization needed to achieve more sustainable P management systems, they indicated that improved management practices and procedures was their top priority ($n = 65$ responses, 19.6% of all responses) (Fig. 5A, Table S13). This was closely followed by new or improved technologies ($n = 55$, 16.6%), new, improved, or different regulations ($n = 54$, 16.3%), and improved approaches for stakeholder engagement ($n = 50$, 15.1%). Next, participants indicated new, advanced materials ($n = 33$, 9.9%), better understanding of current technologies/processes ($n = 32$, 9.6%) were needed, followed by new breeds and varieties of crops and agricultural commodities ($n = 26$, 7.8%). Participants also listed 12 other needs they have to achieve P sustainability, including: alternatives to phosphate food additives, better

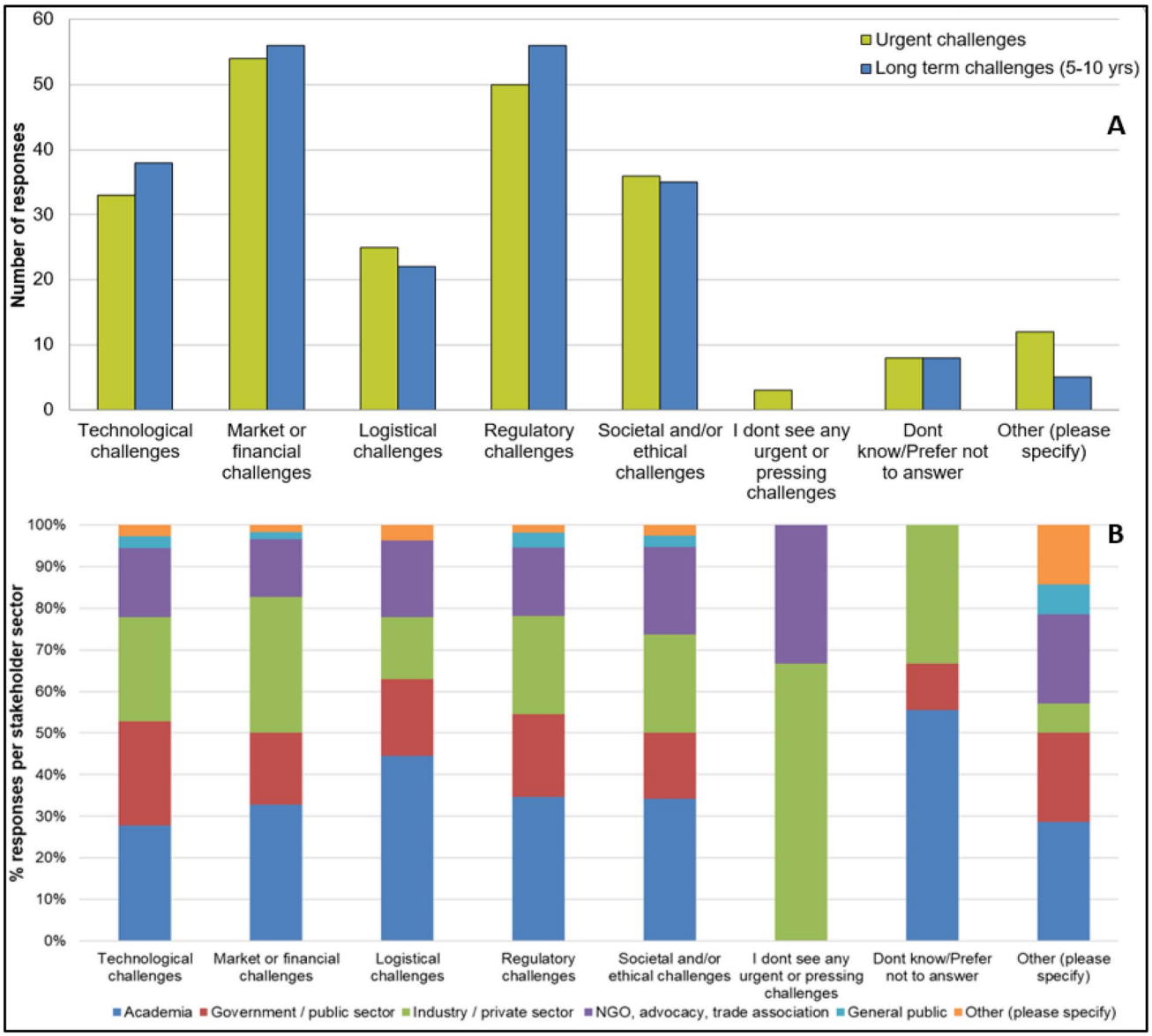

Fig. 4 Challenges for P sustainability according to participants (**A**) and challenges across stakeholder participant sectors (**B**). Responses to **A** "What are the most urgent or pressing challenges that you or your organization currently face in managing phosphorus sustainably?" and "What are some long-term challenges for you or your organization to manage phosphorus sustainably? These include issues that may be less pressing, but need to be addressed in the next 5–10 years." Responses to urgent challenges across stakeholder sectors, shown as % responses per sector (**B**)

litter distribution on crop land, better understanding of the economics, cheaper/more cost-effective solutions, data on cost savings/financial impact, financial support, improved availability/affordability of sustainable P sources, long-term planning on land use, political will, and public investment (Table S13).

When stakeholder responses to needs for achieving more sustainable P management systems were disaggregated by sector, and similar to Fig. 4B, there were generally consistent responses across different sectors (Fig. 5B, Table S14). Only slight differences were observed, where for example, academic participants reported the greatest need for better understanding of current technologies/processes, while government-affiliated participants reported the need for new breeds and varieties of crops/agricultural commodities and industry reported the greatest need for improved approaches for stakeholder engagement.

Developing new or improved technologies is often included in recommendations for improving the sustainability of P management systems (e.g., Scholz et al. 2014; Brownlie et al. 2022). When study participants were asked if they explored or considered the use of new technologies to

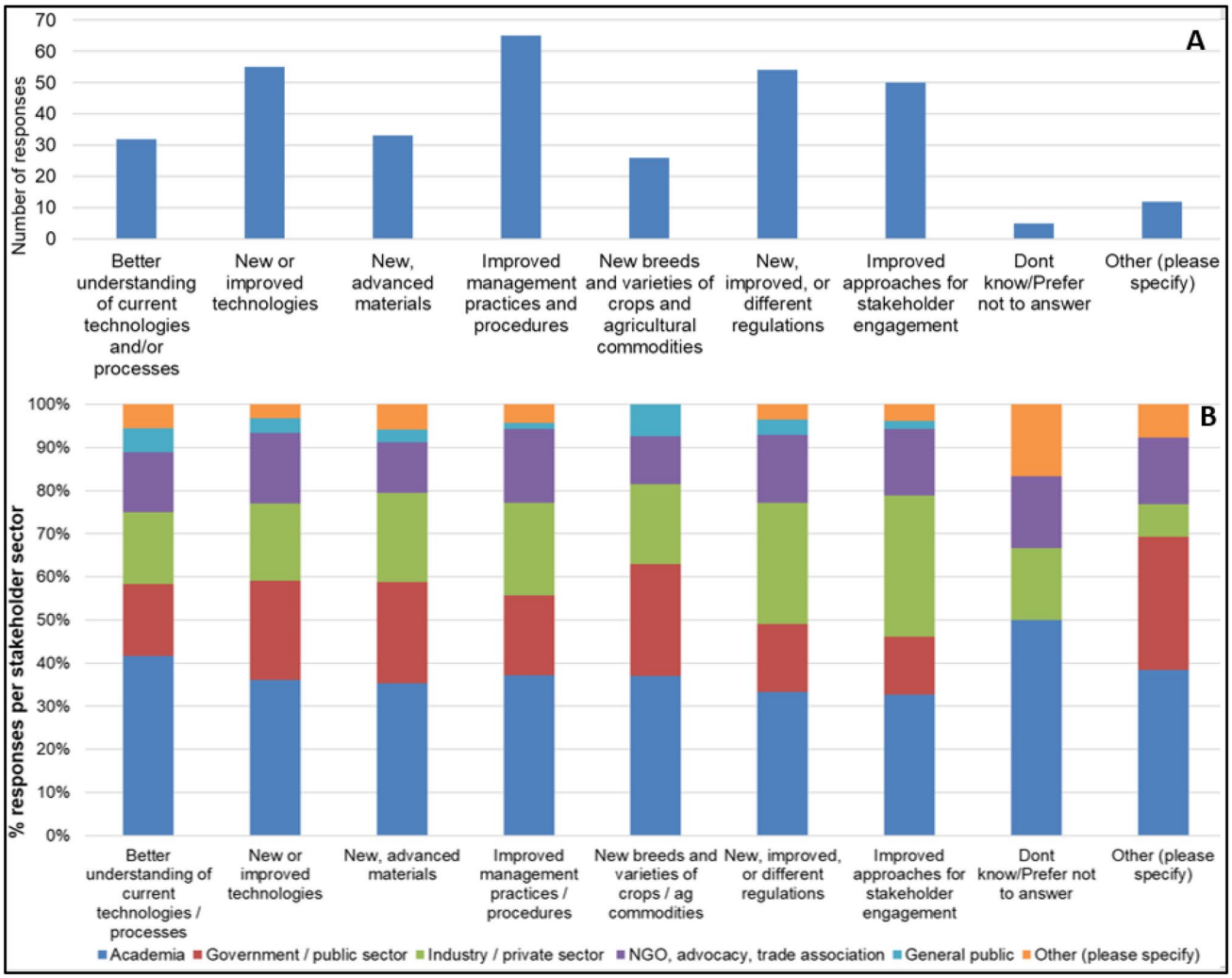

Fig. 5 Stakeholder needs for P sustainability according to participants (**A**) and needs across stakeholder participant sectors (**B**). Responses to **A** "What would help you or your organization achieve more sustainable phosphorus management systems?" Responses to needs across stakeholder sectors, shown as % responses per sector (**B**)

manage P, approximately 70% of respondents indicated they either consider new technologies ($n=58$ responses, 60.4%) or they consider them a little ($n=11$, 11.5%) to manage P (Table S15). When asked to indicate the factors important to participants when considering new technologies to manage P, the main factors were cost and technical performance ($n=63$, 22.3%; $n=59$, 20.8% respectively) (Fig. 6A, Table S16). In addition, ease of use ($n=41$, 14.5%), regulations ($n=39$, 13.8%), stakeholders and/or public perceptions ($n=38$, 13.4%), and convenience ($n=31$, 11%) were also indicated by participants to be factors when considering new technologies (Fig. 6A, Table S16).

When stakeholder responses to questions about factors that were important to them when considering new technology(ies) were disaggregated by sector, there were also consistent responses across sectors for the most part (Fig. 6B, Table S17). There were some minor differences between sectors. Academic and government-affiliated participants indicated that regulation and stakeholder/public perceptions were most important, while industry largely indicated several factors that were important including cost and ease of use, cost, and convenience. (Fig. 6B, Table S17).

4 Discussion

This study responds to a gap in the literature for more empirical data and qualitative analysis of diverse stakeholder perceptions and views of P management systems across a wide range of sectors, geographies, and areas of expertise (Lyon et al. 2020; Martin-Ortega et al. 2022). To the best of the authors' knowledge, this study is among the first to provide

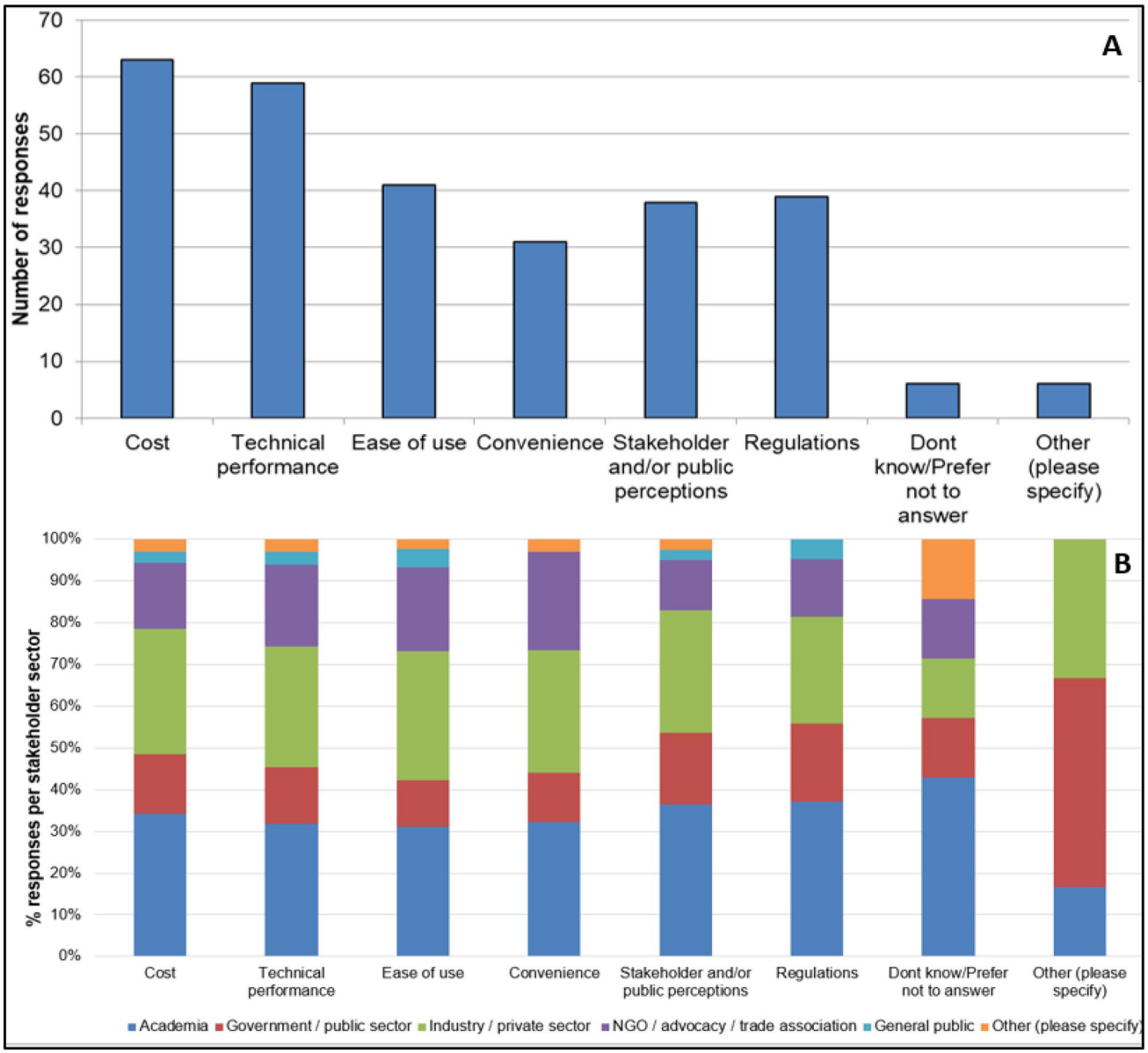

Fig. 6 Factors important to participants when considering new technology(ies) to manage P (**A**) and factors across stakeholder participant sectors (**B**). Responses to "Which of the following factors are important to you or your organization when considering or deciding on a new technology/technologies for phosphorus management?" Responses to considerations across stakeholder sectors, shown as % responses per sector (**B**)

survey data documenting stakeholders' views on P management systems. Based on responses from 96 stakeholder participants from a range of sectors, areas of expertise, and geographies, this study reveals three major findings regarding stakeholder views, needs, and priorities related to sustainable P management.

First, stakeholders largely viewed P management as unsustainable and were generally concerned. We found that there was a statistically significant relationship between views of sustainability and levels of concern; meaning, participants who described P management systems as unsustainable were also likely to report that they were concerned about P sustainability. Perhaps as a consequence of the statistical relationship between the two, stakeholder views of what made P management systems unsustainable and the reasons for their concern were very similar. In both cases, stakeholders emphasized (i) the finite and/or non-renewable nature of P rock resources, (ii) over- or mis-application of P in agriculture, (iii) the need for better P recovery and recycling, and (iv) adverse impacts of P loss on water quality. Because the sample was largely composed of people who described themselves as familiar with P, variations on

views of sustainability and levels of concern could reflect, for example, differences in perspectives or needs across sectors. We find these results to be generally consistent with previous studies that have summarized stakeholder perspectives of P management and sustainability (Cordell 2008; Ulrich and Schnug 2013; Yarime et al. 2014; Jacobs et al. 2017). For example, a number of studies published over the past decade have described the interdisciplinary, complex, and 'wicked' nature of the P sustainability challenge (Cordell and White 2013; Metson et al. 2015; Jacobs et al. 2017). While the P extracted from nonrenewable phosphate rock is an essential resource for society, its inefficient use and mismanagement is detrimental to environmental quality (Schröder et al. 2011; Elser and Haygarth 2020; Nedelciu et al. 2020; Nelson et al. 2021). Many of these studies have identified locations in the P-supply chain that pose the most risk, from mining to use in food and agricultural processes, to dealing with excess P in animal wastes, and wastewater treatment. The stakeholders in this study encompass many of these sectors and the perspectives they offer in their survey answers confirm the findings in these previous studies. Moreover, their responses also reflect concerns about finding appropriate policy solutions across diverse scales and jurisdictions to improve P sustainability across these sectors in the supply chain (Hukari et al. 2016; Rosemarin and Ekane 2016; Garske et al. 2020).

Second, stakeholders reported on a range of challenges and did not generally distinguish between those in near and long-term to manage P sustainably. In both cases, market, financial, and regulatory challenges were most important, followed by societal, ethical, or logistical challenges. These findings indicated that stakeholders largely perceived a common set of challenges to manage P sustainably across sectors and between urgent (current) and long-term (5–10 years) time periods. Many of the challenges identified in these studies overlap with the areas of concerns as listed by stakeholders surveyed in our study, including the finite nature of phosphate rock, the inefficiencies of current use and management, and the need to improve recycling and P circularity particularly to limit/reduce impacts of P pollution on aquatic systems (Childers et al. 2011; Cordell and White 2013; Chowdhury et al. 2017; Peterson et al. 2021). It should be noted that participant responses on key challenges, including those mentioned as "other" by participants, had less emphasis on P supply, access, and equity issues, although these are important when considering P management issues on global scales (Brownlie et al. 2022). This lack of emphasis on access and equity is likely an artifact of the stakeholders who participated in the study, who largely resided in countries where P is overabundant and a pollutant, and where access and affordability of P is less of a concern. By contrast, in the Global South, access to affordable and trustworthy sources of P continues to be a major challenge, which has profound implications for food security and sustainable development (Chowdhury et al. 2017; Langhans et al. 2021).

Third, and related to the previous point, stakeholders indicated they need a range of solutions to achieve sustainable P management, with a focus on improved management practices, new or improved technologies, improved regulation and policies, and better approaches for stakeholder engagement. As with participant responses to key challenges they face, reported needs were similar regardless of how they identified by sector. This consistency in agreement across sectors suggests a high level of alignment in stakeholder perceptions regarding P sustainability challenges and what is needed to address these challenges. Further, when considering new technologies, cost and technical performance were the most important factors. Although cost is always a factor when a prospective user considers adopting some innovative technology or practice, other influences are known to impact adoption decisions (Rogers 2003; Prokopy et al. 2008; Baumgart-Getz et al. 2012). Those influences emerge from the stakeholders we surveyed. For example, stakeholders are also concerned about the technology itself—how easy it is to use and whether it will actually achieve their goals, in this case advancing P sustainability. Adopters are also influenced by social factors, including regulatory pressure and their own social networks (Ribaudo and Caswell 1999).

Overall, findings from this study may be useful for researchers, experts, professionals, regulators, and other decision-makers involved in P management and sustainability. This study provides empirical data on a range of stakeholder perceptions, concerns, challenges, and needs to manage P sustainably based on a range of study participants. Future research studies could leverage these findings to conduct more in-depth analyses of stakeholder perceptions focused on specific stakeholder sectors or within specific geographic areas, particularly to identify barriers and needs related to achieving more sustainable P management solutions or practices. Future research could also investigate statistically significant differences in perceptions or views between stakeholder groups, although larger sample sizes would be needed for robust analyses.

Alongside the main findings from this study, we recognize that there may be several limitations to the approach used. First, this study reports on stakeholder views of P sustainability based on responses from 96 participants, the majority of whom currently worked in P management and were generally familiar with P management issues. Subsequent work could therefore build off this effort to investigate views of more diverse stakeholders who are less familiar with P sustainability and/or not already involved in P sustainability efforts. Second, because of the large percentage of study participants identified as residing in the U.S., these participants may not be representative of stakeholder views in other parts

of the world, due to socio-economic and cultural differences. Third, while there was a total sample size of 96 participants in this study, the number of participants in each stakeholder sector were relatively small, and therefore it was not scientifically sound to conduct statistical analyses across sectors to understand how responses differed. While future studies may focus on expanding the number of participants, especially those not already familiar with P sustainability issues, we find this study to be effective as a first-tiered approach to understand key stakeholder views of P sustainability and associated challenges as well as needs that can be expanded in subsequent research. Finally, the survey was disseminated and conducted using an online survey platform, therefore participants needed access to an internet connection to participate in the study. While this is a potential limitation, we targeted individuals who were professionals and therefore assumed they would have internet access.

5 Conclusion

Alongside research efforts to advance P sustainability have been calls for improved stakeholder engagement and cooperation. While the integration of stakeholder perspectives and needs have widely been considered to be an essential component of developing effective P management solutions, there are comparatively few published studies that report stakeholder perspectives and needs within P-specific contexts. This study therefore addresses this critical need by eliciting diverse stakeholder views, needs, concerns, and challenges regarding P sustainability through the conduction of an online survey. Based on responses from 96 stakeholder participants from a range of sectors, areas of expertise, and geographies, we identified three major themes:

- Stakeholders largely viewed P management as unsustainable and were generally concerned, primarily related to (i) the finite and/or non-renewable nature of P rock resources, (ii) over- or mis-application of P in agriculture, (iii) the need for better P recovery and recycling, and (iv) adverse environmental impacts and especially water quality.
- Stakeholders reported on a range of challenges to manage P sustainability in the near and long terms, with market or financial challenges as well as regulatory challenges considered to be most important, followed by societal and/or ethical challenges and logistical challenges.
- Related to the previous theme, stakeholders indicated they need a range of solutions to achieve sustainable P management, with the strongest need for improved management practices or procedures, new or improved technologies, as well as new or improved regulations and improved approaches for stakeholder engagement.

Overall, results from this study may help inform future research, engagement, and policy priorities to ensure sustainable P management solutions based on stakeholder-identified perspectives and needs.

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Author contributions KG and AM obtained funding for and oversaw the project; KG, AM, AD, and AM designed study; AM disseminated survey, conducted data analysis, coded open-ended responses from stakeholders, and prepared figures; KG prepared and finalized manuscript and revised the figures; AM, AD, and AM provided comments and revisions to manuscript.

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Declarations

Conflict of interest All authors of this manuscript declare there are no conflicts of interest.

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