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PRACTICE BRIDGE

# Engaging stakeholders in phosphorus sustainability: Challenges, lessons learned, and implications for addressing other wicked problems

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To address wicked problems, particularly in sustainability, interdisciplinary solutions that bridge science and society are essential. These solutions inevitably require the involvement of diverse stakeholders. However, the field of stakeholder engagement includes a wide range of approaches, and there is no universally agreed-upon set of standard practices for engagement, particularly in wicked problem contexts. This article addresses this gap by connecting scientific knowledge on stakeholder engagement with an exploration of its challenges, drawing from both the broader literature and the authors' own experiences in sustainability contexts. In particular, this article first identifies and briefly reviews 6 key steps and best practices for stakeholder engagement, and then discusses challenges and lessons learned from engaging stakeholders in the context of phosphorus sustainability largely within U.S. contexts. Phosphorus sustainability is a valuable case study due to its vital role in supporting global agriculture and societal functioning, while also contributing to environmental challenges caused by excess runoff, among other issues. Reflecting on both best practices and our own experiences, we identify 3 key challenges to engaging stakeholders in phosphorus sustainability: (i) managing the inherent tensions between breadth and depth of engagement, (ii) difficulties in evaluating the collective impact of engagement, and (iii) building sufficient capacity in carrying out engagement. To address these limitations, we highlight lessons we have learned in our own engagement efforts and provide recommendations for future research on stakeholder engagement, particularly in the context of wicked sustainability problems.

**Keywords:** Stakeholder engagement, Phosphorus, Sustainability, Wicked problems

## 1. Introduction

Our society currently faces several "wicked problems" related to sustainability. Wicked problems are complex issues that are extremely difficult to solve because of underlying, interconnected factors that may even be challenging to recognize (Lönngren and van Poeck, 2021). Wicked problems share a number of common characteristics, including lack of clear problem definition or endpoint, conflicting values among stakeholders, long-term and diffuse effects in nature, and no generalizable solutions (Rittel and Webber, 1973). Examples of wicked problems include climate change, poverty, health care, and sustainable management of resources, such as phosphorus (P) (Jacobs et al., 2017; Jones et al., 2020; Wiering et al., 2020). In these cases, it is increasingly clear that science and technological innovation alone cannot solve these complex challenges. Rather, interdisciplinary, multi-sectoral solutions that bridge science and society are needed, especially in sustainability contexts (Dentoni et al., 2018; Kuzma et al., 2020; Eaton et al., 2021; Grieger et al., 2022).

Interdisciplinary solutions to wicked problems will inevitably require the engagement of diverse stakeholders and actors (Mease et al., 2018), as these issues arise from complex, interrelated causes that span multiple sectors and groups (Mease et al., 2018). To be effective, engagement strategies should follow established best practices to

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ensure that solutions are identified, prioritized, accepted, and adopted by stakeholders and affected communities (Mease et al., 2018; Franklin, 2020; Kliskey et al., 2021; Grieger and Cummings, 2022; Deviney et al., 2023). To date, there is a broad literature base that describes different practices and examples of engaging stakeholders in different contexts (e.g., Rowe and Frewer, 2005; Colvin et al., 2016; Franklin, 2020). Such processes for stakeholder engagement have been instrumental in both shaping sustainability research and developing solutions in many contexts. For example, in food–energy–water systems research, engaging local stakeholders is essential for contextualizing knowledge of broad-scale systems (Kliskey et al., 2021).

Today, the field of stakeholder engagement has grown and evolved to represent a variety of approaches and methods that differ in their expected goals, methods, time and resource commitments, and expected outcomes (Rowe and Frewer, 2005; Colvin et al., 2016). This variety has led to a lack of a universally agreed-upon set of standard practices for researchers and practitioners to follow (Eaton et al., 2021) as well as varying definitions for the term "stakeholder" (Franklin, 2020; Kliskey et al., 2021). For the purpose of this article, we use the following definitions: (1) "researchers" of stakeholder engagement are individuals who seek to understand, analyze, and enhance engagement processes through research activities, and who may also be involved in developing theories, frameworks, and methods that advance both the practice and scholarly understanding of stakeholder engagement, (2) "practitioners" are those who predominantly apply stakeholder engagement strategies in real-world settings, and (3) "stakeholder" refers to individuals or groups of individuals who affect or are affected by an event, activity, intervention, process, and/or decision (Reed et al., 2009; Franklin, 2020; Kliskey et al., 2021).

This article aims to identify best practices for stakeholder engagement and share insights from their implementation. We begin by outlining 6 key steps for effective engagement, followed by a discussion of common challenges and lessons learned. In particular, we draw from both the broader scientific literature and the authors' own experiences in the context of phosphorus (P) sustainability, largely within U.S. contexts. Phosphorus sustainability is a valuable case study for a wicked problem, given the contradictory role of P in supporting global agricultural production while also sometimes harming critical public goods, including aquatic ecosystems and drinking water sources (Cordell and White, 2014; Jones et al., 2020; Elser and Haygarth, 2021; Elser et al., 2025). Further, managing P sustainability requires the collaboration and engagement of a wide range of stakeholders across various sectors and groups (Deviney et al., 2023; Grieger et al., 2023). The lessons learned through this dialogue could be valuable for addressing other complex, wicked problems in various sustainability contexts including those in other geographic regions.

## 2. Stakeholder engagement

### *2.1. Background and overview*

In the field of stakeholder engagement, stakeholders include those who have direct decision-making power or influence on a given activity, such as regulators or industry decision-makers, as well as those who are impacted by a given activity or decision, such as consumers or diverse public groups (Colvin et al., 2016; Kliskey et al., 2021). Other common stakeholder groups include academic scientists, government officials (at local, regional, and national levels), advocacy groups, nongovernmental organizations (NGOs), trade unions, and Indigenous communities. We recognize that the term "stakeholder" may be objectionable and offensive, given the historical and political contexts from which it is derived (Reed et al., 2024). Other terms such as "partners," "collaborators," and "interested parties" are currently being explored and proposed in the literature, although the field of "stakeholder engagement" does not yet have another term that is widely adopted (Reed et al., 2018; Reed et al., 2024).

"Stakeholder engagement" refers to a process whereby stakeholders are involved in discussions or decision-making regarding events, processes, or interventions that affect them (Aakhus and Bzdak, 2015; Freeman et al., 2017; Reed et al., 2018; Kujala et al., 2022). Today there is a spectrum of different processes of engagement and participation. For instance, processes can passively engage stakeholders (e.g., posters displayed at public events) or consult stakeholders (e.g., quick polls), as well as involve stakeholders more actively (e.g., panels) or include them in two-way discussions or decision-making processes (e.g., workshops to co-design solutions) (Reed et al., 2018). Numerous studies suggest there are many benefits to engaging stakeholders. Some benefits include better aligning research or program agendas with stakeholder needs and preferences, identifying the most relevant problems and appropriate solutions, integrating diverse needs and perspectives into decisions, improving the acceptance and adoption of technologies or management solutions, and helping to create more equitable, just, and fair decisions (Bryson, 2004; Cvitanovic et al., 2015; Franklin, 2020; Grieger et al., 2023). Engaging different stakeholder groups in research or management can also help build consensus, create a sense of shared responsibility, and foster trust in the science or policy driving change, especially when conducted early in the process (Kang and Hustvedt, 2014; Cvitanovic et al., 2015; Lavery, 2018).

While various approaches to stakeholder engagement exist, several researchers have noted that there are no unified or standardized sets of approaches and practices to follow (Yang et al., 2011; Eaton et al., 2021; Kujala et al., 2022). Owing to the great variability in approaches and processes to stakeholder engagement reported in the literature, others have noted that it is challenging to develop a "one-size-fits-all practice" for engagement that can be applied across varying situations (Talley et al., 2016). Furthermore, few studies have examined the effectiveness of various engagement approaches, especially in addressing wicked problems in sustainability (Dentoni et al., 2012; Pryshlakivsky and Searcy, 2013; Dentoni et al., 2018; Hargrove and Heyman, 2020; Eaton et al., 2021; Alexander et al., 2022).

For these reasons, we draw from the peer-reviewed literature to highlight and briefly review some key steps and best practices for stakeholder engagement. Our goal is not to provide a comprehensive review of all engagement methods in every context, but rather to distill the evolving literature into helpful guidelines for practitioners to follow. For more detailed descriptions of engagement see Talley et al. (2016), Kliskey et al. (2021), and Steger et al. (2021).

### *2.2. Key steps and best practices*

**Figure 1** provides an overview of the 6 key steps identified. In addition, **Figure 2** includes a list of guiding questions for researchers or practitioners to use when conducting engagement.

**Step 1 identifies and clarifies the goals for engagement**. Among others, researchers and practitioners can ask themselves: *What do we hope to achieve by engaging stakeholders? How can stakeholders also benefit from being engaged?* There are typically 3 types of goals in engaging stakeholders: (i) sharing information or knowledge (including outreach efforts), (ii) obtaining information or insights (such as stakeholder perceptions, views, attitudes, and concerns), and (iii) co-creating knowledge or solutions (such as co-identifying or developing priorities). Other potential goals may include building trust and improving transparency, enhancing collaborations and partnerships, and improving the implementation of decisions (Castaldo et al., 2010; Kang and Hustvedt, 2014; Eaton et al., 2021). Time, resources, and broader context (e.g., participants' socioeconomic status, ability to participate, cultural norms) can heavily influence the setting of engagement goals (Talley et al., 2016; Gerlak et al., 2023). Therefore researchers/practitioners should ask themselves: *What are the time and resources available for engagement? What are the social, economic, and/or cultural contexts that may shape engagement practices?* It is also possible to combine different goals across a series of engagement activities, for example, conducting a listening session with key stakeholders to obtain feedback or insights that then informs a subsequent engagement activity to co-create solutions with other community members.

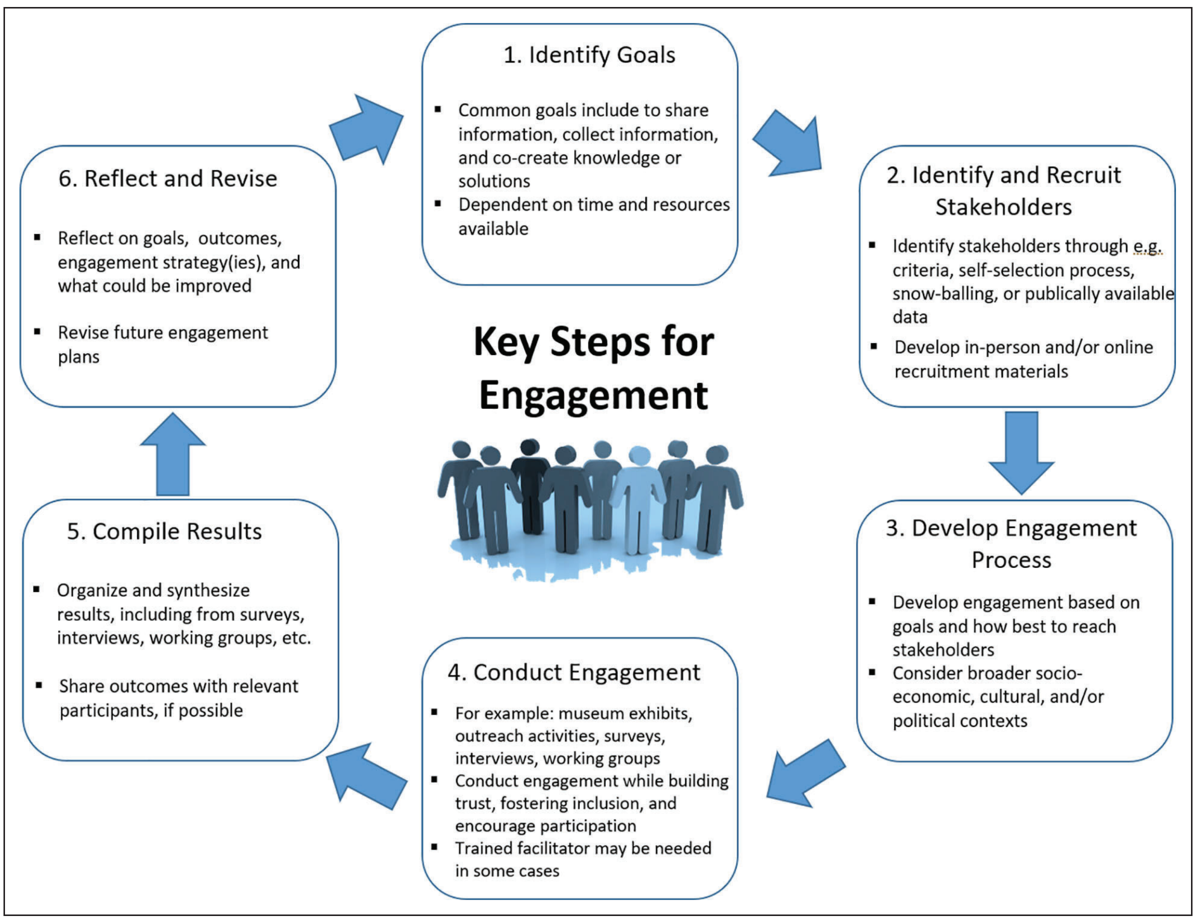


**Figure 1. Key steps for engaging stakeholders.** There are 6 key steps for effectively engaging stakeholders, based on the broader literature on stakeholder engagement. These steps include identify goals for engagement, identify and recruit stakeholder participants, develop engagement process(es), conduct engagement activities, compile results, and reflect and revise for future engagement.

| Step | Guiding questions for researchers or practitioners | Sub-questions |
|---|---|---|
| 1. Identify Goals | What are the goals for engaging stakeholders?<br>What are the resource-levels and socio-economic, and cultural contexts in which engagement will occur? | • What are researchers/practitioners hope to achieve by engaging stakeholders? For example, to share information, collect information, co-create knowledge or solutions, and/or build trust, etc.<br>• How can stakeholders benefit from being engaged?<br>• What are the time and resources available for engagement?<br>• What are the social, economic, and/or cultural contexts that shape engagement practices? |
| 2. Identify and Recruit Stakeholders | Which stakeholders should be engaged?<br>How should stakeholders be recruited?<br>Does trust need to be established with stakeholders before recruitment? | • Who are the stakeholders are affecting a given decision, activity, or event? Who are the stakeholders who are affected by the decision, activity, or event?<br>• How can stakeholders be identified? For example, use of criteria, self selection processes, snowballing, publicly available literature or data<br>• How can targeted stakeholders be reached and recruited, for instance through in-person (e.g. flyers) or online (e.g. email, social media) methods? |
| 3. Develop Engagement Process | Which engagement activities are best to meet the goals for engagement?<br>Do stakeholders need incentives to participate? | • Which activities engage stakeholders in a way that meets the engagement goals, and within time and resources available?<br>• Options include: public displays, science museum exhibits, extension events; surveys, interviews, focus groups; collaborative working groups, advisory boards; citizen advisory committees, public meetings, roundtables, Delphi studies |
| 4. Conduct Engagement | During engagement, do activities or settings need adjusting? | • Have researchers/practitioners implemented real-time monitoring of engagement activities?<br>• Do activities or settings need adjustment during engagement?<br>• If so, can facilitator(s) and/or organizers create necessary adjustments to ensure goals of engagement are achieved? |
| 5. Compile Results | After compiling results, how can results be disseminated? | • After engagement, should generated results be disseminated or shared with participants, if applicable?<br>• If so, do aspects of confidentiality and privacy need to be considered? |
| 6. Reflect and Revise | After completion, how can engagement strategies be improved in the future? | • After engagement, did the engagement activity/ies achieve the goals?<br>• Were the "right" stakeholders identified and engaged during the activity/ies?<br>• How should the engagement activity(ies) be improved in the future, if applicable? |

**Figure 2. Guiding questions for researchers or practitioners for leading engagement activities.** In each of the 6 steps to engaging stakeholders, there are several guiding questions for researchers or practitioners to use when conducting engagement to help ensure a successful engagement process.

**Step 2 involves stakeholder identification and characterization**. At this step, researchers and practitioners should ask themselves: *Which stakeholders are important to engage to achieve the identified goals?* A thoughtful, deliberate, and transparent approach is needed to identify and target stakeholders for engagement. Several frameworks exist to support this process including, for example, the Means, Motive, and Opportunity framework for stakeholder agency (Bird et al., 2022), the stakeholder analysis matrix (Kennon et al., 2009), or the Power-Interest Grid (Ackermann and Eden, 2011). Such frameworks ensure adequate breadth and awareness of relationships between potential stakeholder groups. The type and total number of stakeholders involved will be largely context dependent. Some contextual characteristics include the goals of the engagement activity, the broader environment in which the engagement occurs, and time and resource constraints. In relatively simple situations, only a few different types of stakeholders may need to be engaged, whereas more complex and uncertain issues will require many more stakeholder groups to be involved (Florin and Parker, 2020). Stakeholders (both individuals and groups) can be characterized according to their ability to affect or be affected by a given project, decision, activity, or event, differing needs or perspectives, sectors (e.g., industry, government), geographies, areas of expertise or interests, and so on.

Various approaches exist to identify targeted stakeholders, such as (i) application of predetermined criteria for inclusion (e.g., geography, interests, degree of influence or decision-making power), (ii) self-selection processes in which stakeholders can volunteer via announcements or advertisements, (iii) referrals from consultants or other stakeholders or experts, (iv) snowballing, a form of chain sampling in which an initial group of "seed" stakeholders leverages their networks to recommend additional participants, thereby expanding the sample size, and (v) using publicly available literature or data (e.g., peer-reviewed articles, census data). Once stakeholders are identified, analyzed, and characterized, recruitment materials are developed and disseminated using approaches that best reach the targeted audiences. Researchers and practitioners should ask: *How can targeted stakeholders be reached and recruited?* Dissemination should occur after the engagement process planning is finalized. In some cases, it may be critical to build and maintain trust with stakeholders prior to disseminating recruitment materials, such as through transparent communication and opportunities for meaningful participation. Dissemination methods could include both physical (e.g., fliers, pamphlets) and virtual (e.g., email, social media) approaches.

**Step 3 develops the engagement processes and activities in a way that best meets the goals of engagement** while considering the time and resources of researchers or practitioners as well as the stakeholders, and their broader socioeconomic, cultural, and political contexts. Researchers and practitioners can ask: *Which activities engage stakeholders in a way that meets the goals, within the time and resources available?* Common activities for sharing information or knowledge include, for example, outreach activities, such as posters at public events, science museum exhibits, and agricultural extension events. Surveys, interviews, and focus groups can be used to generate information or insights from stakeholders, while collaborative working groups or advisory boards can serve as mechanisms to co-create knowledge or solutions with stakeholders. Other engagement activities include expert panels, citizen advisory committees, citizen juries, consensus conferences, public meetings, roundtables, and Delphi studies (Renn, 2015). A trained facilitator may need to be included in the planning and execution phases, particularly for developing focus groups, collaborative working groups, or other activities that involve substantive or structured discussions between participants with differing perspectives.

In this step, researchers and practitioners should also ask: Do stakeholders need incentives to participate in the engagement activities? And if so, what kind of incentives will encourage participation? Participants may be incentivized by using items, such as financial honoraria, gifts, swag (e.g., pens, notepads), or free tickets to events, or by intangible incentives such as recognition from serving on expert panels or citizen advisory committees or being a part of community-based decision-making processes. In addition to incentives for individuals, it may also be important to identify incentives for organizations involved in engagement. These incentives can go beyond providing direct or indirect benefits and may need to align with an organization's underlying motivations, needs, or concerns related to the topic of engagement (Hester et al., 2010; Cantelmo et al., 2022). For example, some organizations or stakeholders may be more inclined to participate if they perceive the process or outcomes directly affecting their organization or their reputation. Others may be motivated to participate if they have access to new or different information, enjoy opportunities for networking, and/or can shape the outcomes of engagement.

**Step 4 is where the stakeholder engagement activities are conducted**. During the activities, researchers and practitioners can ask themselves: *Do the activities or settings need adjustment to improve participation or engagement?* Implementing a system or approach for monitoring and adapting is important in this step to assess how well the engagement is proceeding in real time. For example, groups may benefit from being redirected to a set of discussion questions, among other real-time adjustments. Organizers may benefit from periodically checking in with facilitators to ensure that engagement activities are on track, desired outcomes are being achieved, and all participants are fully included. Once engagement activities end, exit surveys can be used to assess participant satisfaction and to gather additional insights or feedback to improve future engagement efforts.

**Results and other key findings are compiled and synthesized in Step 5**. This stage may involve organizing, analyzing, and synthesizing qualitative and/or quantitative results from surveys, interviews, focus groups, or other activities. Sharing results with stakeholder participants, or in some cases allowing participants to review quotes or transcripts from their own interviews, may also be beneficial in some situations (Stahl and King, 2020). This member checking practice enhances the validity and credibility of research findings and outcomes. In other cases, acknowledging the stakeholders engaged in the activity (especially if reporting the results later) may be important, although confidentiality and privacy also need to be considered.

**Step 6 reflects on the process and identifies areas of improvement**. Organizers may benefit from asking themselves: Did the engagement activities achieve the goals? Were the "right" stakeholders engaged? Did the outcome fit expectations? And how should the engagement activities be improved in the future? Findings from this reflexive process can also support study credibility by acknowledging possible researcher biases, as well as improve future engagement activities.

Multiple challenges can arise at any point during the engagement process. These challenges could include having insufficient time and/or resources to carry out meaningful engagement, unclear or undefined goals of engagement, stakeholders that do not represent all impacted parties, lack of robust participation by stakeholders, lack of meaningful interaction and engagement with participants, stakeholder apathy or fatigue, and lack of trained facilitators or staff to deliver engagement activities (Haddaway et al., 2017). Planning and practice need to take these challenges into account to lessen their possible impact on engagement activities.

## 3. Engaging stakeholders in phosphorus sustainability

The sustainable management and use of the element phosphorus (P) poses a wicked problem that requires the engagement of diverse stakeholders. P is essential for all living organisms. Through its inorganic form of orthophosphate, P plays a crucial role in plant growth, making it a key component in fertilizers and driver of crop production (Elser et al., 2007; Elser et al., 2025). Today, countries worldwide depend heavily on P, due to its critical role in agricultural fertilizers that sustain global crop yield growth and help ensure food security (Cordell et al., 2009; Sharpley et al., 2018). In addition, P is vital to various industrial processes and consumer products, such as water treatment and food products. Several inefficiencies in the use and management of P also threaten its long-term sustainability and adversely impact the environment. For instance, the overapplication of fertilizers in agriculture has led to accumulation of P in soils (Zhou and Margenot, 2023) and leads to runoff that causes eutrophication, harmful algal blooms, and marine dead zones (Jarvie et al., 2015; Riza et al., 2024). Further, P is predominantly extracted from nonrenewable phosphate rock, whose economic production is limited to a relatively few locations worldwide (Cordell et al., 2009; USGS, 2025). Access to P can therefore be constrained by geopolitical and economic barriers. Studies have shown that the unsustainable management of P is expected to worsen as global population increases and diets shift to include more meat (Cordell and Neset, 2014).

The challenges associated with P management are complex, seemingly intractable, have high degrees of uncertainty, and are contested by diverse stakeholders with differing priorities—all of which lead to the "wickedness" of the P sustainability challenge (Cordell and Neset, 2014;

Jacobs et al., 2017; Elser and Haygarth, 2021). For example, agricultural stakeholders, including farmers, may be more focused on P fertilizer application rates to ensure they have robust crop productivity, while environmental researchers and advocacy groups may be more concerned about ecological implications of P runoff into the environment. Other stakeholder groups involved in P management may have other, contrasting views and needs to create sustainable P systems, which further contribute to the need for coordinated engagement efforts to bring together these diverse stakeholders to effectively and sustainably manage this critical resource (Deviney et al., 2023).

In response, various national and international research efforts have been dedicated to improving P sustainability (Metson et al., 2016; Nesme et al., 2018; Drohan et al., 2019; Amgain et al., 2022; Crane et al., 2024). An overview of a variety of coalitions and stakeholder-centered organizations launched over the last 2 decades is shown in **Figure 3**. Among other examples, the Southern Extension and Research Activity (SERA)-17 in the United States was established in 2003 to develop and promote strategies for enhancing P sustainability, particularly where soil and aquatic environments intersect with agriculture (Macrae et al., 2024). The Global Phosphorus Research Initiative emerged a few years later to investigate the role of future P availability on global food supplies. In 2013, the European Sustainable Phosphorus Platform (ESPP) was formed and serves as a platform for industry, universities, and policymakers to discuss P recovery technologies (Catalogue of Nutrient Recovery Technologies) and data needs related to P flows (Data on Nutrients to Support Stewardship; ESPP, 2024).

More recently, the "Our Phosphorus Future" project operated from 2017 to 2021, culminating in a final project report that involved more than 100 researchers from various institutions worldwide (Brownlie et al., 2022). The Sustainable Phosphorus Alliance (SPA) is an industry-focused organization that formed from the U.S. National Science Foundation (NSF)-funded Phosphorus Sustainability Coordination Network that aims to catalyze the emergence of innovations that advance P sustainability in many contexts (SPA, 2024a, 2024b). As a final example, the Sustainable Phosphorus Summit (SPS) is an international conference on P sustainability that has been held at various years and in varying geographic locations over the past 15 years.

Building on these past efforts, in 2021, the U.S. NSF funded a large research center dedicated to tackling P sustainability—the Science and Technologies for Phosphorus Sustainability Center (STEPS, 2024). Led by North Carolina State University with many additional partners across the United States, STEPS is a convergence research center that conducts fundamental and applied research across diverse disciplines and spatial scales to address the wicked nature of the P sustainability problem. Examples of this research include better understanding how phosphates behave at the nano- and micro-scales and how different materials can capture and recover P, for example, Hutchison et al. (2023) and Hussein et al. (2024). STEPS research is also conducted at the spatial scales at which humans interact with new technologies, such as the following: understanding biological P removal processes in wastewater treatment facilities (Mallick et al., 2023; McLamore et al., 2023), capturing P from human urine in buildings (Crane et al., 2024), and assessing how policies and changing diets can influence P sustainability (Wu et al., 2022). Given the wicked nature of P sustainability challenges in which new science and technologies cannot present solutions in isolation, research has also been conducted to identify key stakeholders, including those already engaged, and those not yet involved in

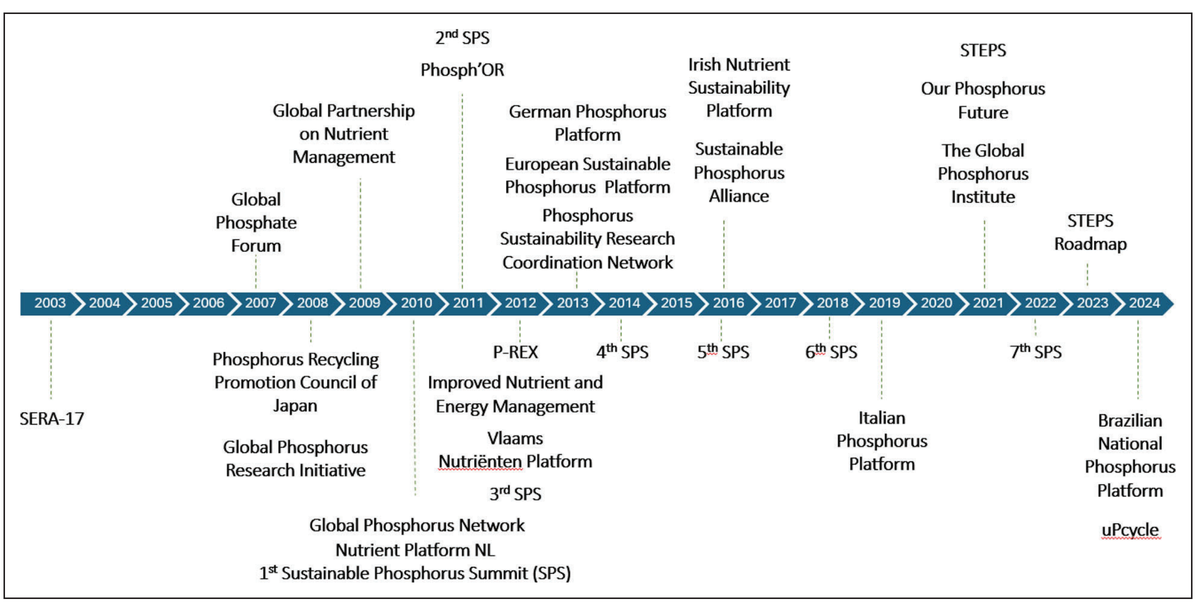


**Figure 3. Timeline of various international initiatives, coalitions, and stakeholder-centered organizations focused on P sustainability.**

engagement efforts (Deviney et al., 2023; Merck et al., 2023) and to elucidate their perceptions of, and needs in, achieving P sustainability across diverse sectors (Grieger et al., 2023; Merck et al., 2024a; Merck et al., 2024b).

STEPS also develops specific mechanisms to engage stakeholders through its knowledge transfer program. Developing and carrying out these mechanisms corresponds to steps 1–6 of **Figures 1** and **2** that are implemented in specific projects and within specific contexts. Overall, the STEPS model of knowledge transfer aims to facilitate the multidirectional exchange of scientific and technical information across a range of sectors and across diverse stakeholder groups, by developing processes for "forward" and "reverse" knowledge transfer and for co-creating solutions (**Table 1**). Forward knowledge transfer refers to sharing knowledge and information from STEPS researchers to external stakeholders, while reverse knowledge transfer refers to eliciting information or insights from stakeholders and bringing information back to the STEPS researchers. STEPS knowledge transfer also has a third goal of co-creating knowledge or solutions between researchers and stakeholders, which blends aspects of forward and reverse knowledge transfer. Note these knowledge transfer goals align with step 1 of **Figures 1** and **2**.

After clarifying the goals of engaging stakeholders, STEPS carries out a range of activities and events to accomplish its knowledge transfer goals, with examples provided in **Table 1**. Examples of forward transfer activities in STEPS include hosting and conducting in-person agricultural extension outreach activities (such as field days) to share information regarding best practices for P fertilizer applications with growers as well as developing online training on P sustainability for agricultural extension agents. Other examples include developing in-person and online outreach materials for the general public, such as presentations and posters displayed at public science fairs on P and its role in sustainability, webinars, and fact sheets that outline actions that individual members of the public can take to improve their P sustainability footprint (SPA, 2024a). There are academic outreach activities for academics, government officials, industry representatives, utility operators, and NGOs. These outreach efforts include conference presentations and hosting of workshops, conferences, and meetings such as the Phosphorus Forum (2022–2025) and SPS (2022, 2025), among other symposia that have included extensive stakeholder attendance. To provide more details of these events, the STEPS Center hosted SPS and co-hosted the Phosphorus Forum in 2022, combining the 2 events into a weeklong event known as "Phosphorus Week" that was held in Raleigh, North Carolina. This combined event attracted over 225 stakeholder participants from a range of sectors, including academia, government officials from federal agencies, government officials from local government agencies, environmental nonprofits, food industry, fertilizer industries. Phosphorus Week consisted of a series of oral and poster presentations, panel discussions, as well as interactive sessions with participants. Hosting "Phosphorus Week" in 2022 was a major knowledge transfer event aimed at sharing and exchanging the latest research on P sustainability among researchers and other stakeholders.

Reverse knowledge transfer activities at STEPS include conducting stakeholder workshops and focus groups to understand perceptions of novel agrifood technologies in securing more sustainable agricultural systems, as well as conducting stakeholder surveys and interviews to identify perceptions, concerns, and needs related to P sustainability (Grieger et al., 2023; Merck et al., 2024b). In addition, STEPS also conducts reverse knowledge transfer by hosting and facilitating stakeholder workshops to identify research priorities and needs. For example, STEPS hosted and facilitated an intensive, intersection series of sessions during Phosphorus Week in 2022, where stakeholder participants from across multiple sectors came together to discuss, identify, and prioritize key research needs for achieving P sustainability. The resulting output of this effort culminated in the development of the STEPS report that identifies top research priorities, called "A Roadmap Toward U.S. Phosphorus Sustainability" (STEPS, 2023).

Further, to co-create knowledge or solutions, the knowledge transfer program builds technical working groups that involve both STEPS researchers and external stakeholders. These groups identify research areas of common interest and value and co-create solutions. For example, recent technical working group topics have included biological P removal in water resource recovery facilities and broader nutrient management. In one such group, STEPS researchers partnered with wastewater facility managers in North and South Carolina to identify key research needs related to improving biological P removal. During their meetings, stakeholders highlighted the need to better understand P removal upsets by enhancing data collection and enabling data sharing across facilities. In response, STEPS facilitated a collaborative process to co-develop a project that directly addressed these priorities, aligning more closely with stakeholder needs for improving biological P removal. Funds were then allocated by the Center to undertake this co-developed research and facility managers provided preexisting data and access to their facilities for new data collection. Other activities to co-create solutions with stakeholders include hosting and facilitating stakeholder meetings, focused on data needs for P sorption and water quality as well as identifying lakes in the United States that may be prioritized for remediation due to eutrophication concerns.

Some outcomes generated from these stakeholder engagement activities include written publications, such as peer-reviewed scientific articles, fact sheets, the STEPS roadmap report (STEPS, 2023), and other outreach materials, as well as presentations, webinars, online videos, and social media posts. Other outcomes are more process-based, such as orchestration of stakeholder workshops, meetings, and extension field day events, in addition to surveys, interviews, and focus groups with stakeholders. Since its launch in late 2021, the STEPS Center has engaged several thousand stakeholders each year through its outreach, extension, and engagement activities.

**Table 1. Overview of stakeholder engagement activities in the Science and Technologies for Phosphorus Sustainability (STEPS) Center**

| Goal | Stakeholders Engaged | Activities Conducted | Outcomes Achieved |
|---|---|---|---|
| **Forward knowledge transfer** (i.e., share knowledge from researchers to stakeholders) | • Academic researchers<br>• Agricultural stakeholders (e.g., growers)<br>• Extension agents<br>• General public<br>• Government officials<br>• Industry representatives<br>• Students (K–12, college)<br>• Utility operators | • Agricultural extension outreach and trainings (e.g., field days, online training modules)<br>• Publications<br>• Presentations (e.g., conferences, seminars)<br>• Public outreach (e.g., science fair)<br>• Scientific conferences and meetings<br>• Webinars, podcasts, video abstracts, social media | • 2,500 stakeholder participants attending extension outreach and training per year<br>• 8,000 K–12 students and teachers per year through educational outreach<br>• 50 peer-reviewed publications<br>• 50 conference presentations per year (e.g., AGU, ASABE, SRA, P Forum, Sustainable Phosphorus Summit)<br>• 50 online videos through Sustainable Phosphorus Alliance YouTube video series<br>• Daily or weekly social media posts (LinkedIn, X, Instagram) with >1,615 followers |
| **Reverse knowledge transfer** (i.e., elicit insights from stakeholders) | • Stakeholders from diverse sectors across P value chain, including<br>  ○ Agricultural stakeholders<br>  ○ Building managers<br>  ○ Government officials<br>  ○ Sustainability leaders<br>  ○ Water district managers | • Roadmapping and priority identification (for P sustainability)<br>• Stakeholder workshops (e.g., nutrient flows, management, novel technologies in food and agriculture)<br>• Stakeholder surveys, interviews, focus groups | • 2023 STEPS roadmap report “A Roadmap Toward U.S. Phosphorus Sustainability,” based on stakeholder input (STEPS, 2023)<br>• 3–5 stakeholder workshops organized per year<br>• Stakeholder survey conducted across groups and sectors in P value chain (Grieger et al., 2023), across academic sustainability offices (Grieger et al., 2025)<br>• Stakeholder interviews conducted related to 3 STEPS projects: Biological P removal, P recovery from human urine, isotope tracing methods (Grieger et al., 2023)<br>• Focus groups on views of novel technologies in food and agriculture |
| **Co-create knowledge or solutions** with stakeholders | • Academic researchers<br>• Agricultural stakeholders<br>• Consultants<br>• Extension agents<br>• Government officials (e.g., federal, state)<br>• Industry representatives<br>• Instrumentation facility operators<br>• Utility operators | • Stakeholder workshops (e.g., data needs for P sorption, water quality)<br>• Technical working groups (e.g., biological P removal in wastewater, nutrient management) | • In-person co-production workshop focused on surface waters of the NC High Country, held at Appalachian State University, May 2024<br>• Technical working group workshops focused on improving biological P removal, held in-person at NC State University, October 2023 and 2024, and online August 2024 |

## 4. Key challenges, lessons learned, and implications for engaging stakeholders in wicked problems

Reflecting on our review of best practices for engagement and our own STEPS experiences in engaging stakeholders in P sustainability contexts in the U.S. societal context, we now identify 3 key challenges and associated lessons we have learned from this work. These lessons may be useful for future engagement efforts focused on P sustainability, including those in other regions of the world and may also be relevant for other wicked problems in sustainability more broadly.

### *4.1. Managing inherent tensions between breadth and depth needed for engagement*

One of the main challenges we find in engaging stakeholders in P sustainability is finding the right balance of breadth and depth of both the number and types of stakeholders to engage for successful impact and what is feasible within given time and resource constraints. In the case of P sustainability, the P value chain spans a vast range of sectors and stakeholder groups. Sectors include, for instance, mining and fertilizer industries, water and wastewater treatment facilities, animal waste and manure management, growers, food retail, composting facilities, among others (Merck et al., 2023). Within each of these sectors, there are also distinct stakeholder groups who are affecting and/or affected by P management. These groups include academia, industry, government, NGOs, advocacy groups, diverse publics, Indigenous communities, and other groups (Lyon et al., 2020; Grieger et al., 2023). Following best practices for engagement, each of the stakeholders across various sectors and groups should be engaged in some capacity, such as receiving information or knowledge (forward knowledge transfer), providing insights or information (reverse knowledge transfer), and/or co-creating knowledge or solutions together, particularly in cases of decision-making. However, because of the vast number and diversity of stakeholders in P sustainability, a key challenge is deciding which particular stakeholders to engage, given that it would take an enormous amount of time and resources to engage all impacted stakeholders related to P sustainability. Furthermore, some stakeholders may not see value in participating, may not have enough resources to dedicate to engagement, or may send representatives who are ill-equipped to contribute meaningfully. Indeed, in most cases, it is not feasible to engage all stakeholders, at least not at the same time and not with the same intensity levels. As a result, decisions must be made about the depth and breadth of stakeholders to include in engagement efforts (particularly in engagement step 2, but can be relevant for steps 1, 3, and 4 discussed above)—decisions which may be more difficult in wicked problems that involve diverse and interconnected sectors and groups compared to more simple problems (Florin and Parker, 2020).

Step 1 aims to define the goals of engagement. In STEPS, we have decided to engage stakeholders at 2 levels to accomplish 2 separate goals. Our first goal was to share knowledge about P sustainability with a wide range of stakeholders, including the public, to build community and raise public awareness of the broader issues related to P sustainability. We accomplished this through various informal outreach activities, such as giving talks and developing social media campaigns and factsheets (i.e., forward knowledge transfer) (**Table 1**). These engagements tended to be one-way transfers of information from the Center outward and generally required minimal resources.

Our second goal was to facilitate focused changes by engaging stakeholders who have decision-making power, such as representatives from industry and government. The choice to focus on decision-makers reflects our charge as a science and technology research center, which is to develop technical and policy innovations for decision-makers and leaders who can facilitate sustainability changes within the P value chain. More intensive, bidirectional engagement was targeted at stakeholder groups who were highly invested in the outcomes of specific research projects within the Center. These groups were addressed through mechanisms such as surveys, interviews, focus groups, trainings, and workshops (Grieger et al., 2023; Merck et al., 2024b; Grieger et al., 2025). For instance, we surveyed 96 stakeholders from a range of sectors, expertise, and geographies to understand perceptions and needs for achieving P sustainability (Grieger et al., 2023), and also surveyed 65 stakeholders from U.S. academic sustainability offices to understand their views of water conservation and sustainability practices (Grieger et al., 2025). Further, we conducted 37 interviews with stakeholders related to P recovery technologies to identify barriers and driving forces for achieving P sustainability in the United States (Merck et al., 2024b) and engaged a small subset of stakeholders in collaborative working groups to co-create solutions related to P removal in wastewater facilities and to prioritize lakes for nutrient management interventions (Megdal et al., 2017; Grieger et al., 2023).

Based on these experiences, future engagement efforts can build on these lessons learned when deciding on how best to balance breadth and depth of engagement (i.e., breadth in broader outreach, depth in specific projects with targeted stakeholders). Going forward, community-based engagement should be prioritized to ensure that a broader array of stakeholder groups is reached. This type of engagement will further integrate communication, education, and outreach between investigators and community-based groups to increase knowledge and awareness of P management issues and strategies.

### *4.2. Difficulties in evaluating the collective impact of engagement*

Having engagement efforts spread across both the breadth and depth of stakeholders within the wicked sustainability problem of P also presents another challenge of effectively gauging or evaluating the collective impacts of engagement. As shown in **Table 1**, we have documented the number of stakeholder participants we have engaged in various activities (e.g., >2,500 stakeholders through extension outreach/training each year, >8,000 K–12 students and teachers through educational outreach each year), along with the number of publications, presentations, and workshops hosted. However, how impact is assessed—usually associated with steps 4 (conduct engagement), 5 (compile results), and 6 (reflect and revise)—depends on the purpose of the engagement (i.e., step 1, identify goals). For example, the effectiveness of social media awareness campaigns may be evaluated using the number of views or followers, while the effectiveness of workshops can be evaluated through participant exit surveys. It is more challenging, however, to evaluate the collective impact of engagement in metrics such as stakeholders adopting new technologies or practices, as there are many (confounding) factors that drive adoption.

One key lesson learned from this experience is that better ways to evaluate near-term impact of engagement are needed, particularly to understand if engagement efforts have been successful or if other approaches would have been better to make changes. For starters, researchers and practitioners could follow the guiding questions and sub-questions in **Figure 2** throughout steps 1–6 to assess their engagement plans and activities. This may help ensure that goals are met (step 1) and that any insights gained during the planning and implementation phases (steps 3, 4, and 5) are captured and incorporated into future engagement efforts (step 6). Additionally, when a series of stakeholder engagement activities is planned, engagement goals could be tracked and refined annually or biannually to support ongoing adaptation and improvement. The need for implementing steps to gauge effectiveness of engagement throughout engagement cycles is especially true for wicked problems such as P sustainability that span diverse sectors and groups and tend to operate on medium- to long-term time scales. We note here that this need for implementing approaches to measure effectiveness is not necessarily unique to the field of P sustainability, but rather is well-documented for the field of stakeholder engagement in general and an area that warrants further attention more broadly (Tomkiv et al., 2019; Kliskey et al., 2021).

### *4.3. Challenges in building sufficient capacity in carrying out engagement*

As mentioned, it is important to aim for both broad and deep engagement activities to reach as many impacted stakeholders in wicked problems as possible. Such a balanced approach requires resources (including time, funding), as well as having qualified and trained practitioners to develop and implement engagement activities that span steps 1–6. In wicked problems, critical decisions will need to be made on how best to meet the potentially large demands for engaging diverse stakeholders across a range of sectors and groups, often within limited resource constraints.

One approach to meeting these engagement demands is to hire social scientists or practitioners with engagement experience and train them in the more technical aspects of the wicked problem (such as P sustainability). For a problem of this magnitude, this would require additional resources beyond those available in a single research center, especially those that are predominantly STEM-based. In the STEPS Center, we initially relied on this approach to engage diverse stakeholders in forward and reverse knowledge transfer activities, including those that focus on co-creating knowledge or solutions. Another approach is to "democratize" stakeholder engagement, by educating and training a subset of more technical researchers and students (including those in STEM fields) in best practices for engagement, or pair them with social scientists, interdisciplinary researchers, and/or practitioners who are trained and familiar with engagement work. In STEPS, we facilitated this approach by developing guidance and training materials and providing hands-on support to researchers, to expand the capacity for engagement in the Center. As one example, STEPS researchers (i.e., environmental engineers) in the technical working group on biological phosphorus removal received hands-on, tailored training on stakeholder engagement best practices for them to engage with wastewater facility managers and operators. This training equipped them with the knowledge and skills needed to effectively apply these practices while conducting the technical working group.

One lesson learned from this challenge is that choosing one or both of these approaches (among others) presents trade-offs in terms of how best to develop the capacity for engagement in complex wicked problems (with associated decisions on how best to use available resources), especially given that there are structural challenges in developing this capacity within current organizational systems (Talley et al., 2016; Potts, 2020; Eaton et al., 2021). For example, conducting engagement and outreach is rarely a programmatic feature of core graduate training programs. Nor are faculty without extension appointments typically incentivized to undertake such engagement and outreach as part of the tenure process. Engaging stakeholders also takes substantial amounts of time, including establishing relationships and building trust with stakeholders, planning and conducting engagement activities, and analyzing results—and this time takes away from pursuing outputs that are typically used in traditional reward systems (e.g., publications, patents, grants). In STEPS, we have provided incentives to encourage researchers and students to involve stakeholders in projects including additional funding, resources, and recognition. However, the current organizational structures and systems in which faculty and students operate often prioritize traditional metrics or reward systems that may not fully support or align with effective stakeholder engagement related to P sustainability contexts. For these reasons, one key lesson learned from this challenge is that there may need to be a reassessment of reward systems for students, researchers, and faculty to develop capacity to meaningfully engage stakeholders to help solve wicked problems.

## 5. Conclusions and outlook

Despite the enormous importance of engaging stakeholders in interdisciplinary solutions to help solve complex wicked problems, the existing literature presents a wide variety of approaches and methods, with no universally accepted set of best practices. This Practice Bridge aims to link scientific knowledge on stakeholder engagement with an exploration of its challenges, drawing from both the broader literature and our own experiences in P sustainability contexts. After reviewing 6 key steps and best practices for stakeholder engagement that can be applied to various circumstances, including those in sustainability contexts, we highlight 3 key challenges and subsequent lessons learned from our experiences in engaging stakeholders in P sustainability. These include managing the inherent tensions between breadth and depth of engagement, dealing with difficulties in evaluating the collective impacts of engagement, and addressing challenges in building sufficient capacity in carrying out engagement. While our experiences are largely placed within the U.S. context, the identified challenges and lessons learned may be applicable or relevant to other regions. By sharing these insights, we hope to support and strengthen the efforts of other researchers, scholars, and practitioners working to engage stakeholders in P sustainability and other wicked problems.

Looking ahead, we recommend advancing research in developing methods and best practices for tracking and monitoring stakeholder adoption practices and policy changes over time. Further research could also help develop methodologies for optimizing both costs and the number and types of stakeholders needed for specific classes of engagement activities. Given the wide range of engagement methods available, more research is also needed to determine the most suitable approaches to achieve the desired goals within the specific contextual circumstances. The outcomes of this research could help researchers and practitioners more easily identify the most effective strategies for driving change in the context of wicked problems.

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The authors declare no competing interests.

## Author contributions

- Contributed to conception and design: KG, NB, KB, AD, JJE.
- Contributed to acquisition of data: KG, NB, KB, AD, MS, JJE.
- Contributed to analysis and interpretation of data: KG, NB, KB, AD, MS, JJE, JLJ.
- Drafted the manuscript: KG, NB, KB, AD.
- Revised the manuscript: KG, NB, KB, AD, JJE.
- Approved the submitted version for publication: KG, NB, KB, AD, MS, JJE, JLJ.

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