ABSTRACT

NIEUWSMA, JULIANNA. The Wicked Challenge of Phosphorus Sustainability: Using Education to Disrupt the Status Quo (Under the direction of Dr. M. Gail Jones).

There is a sustainability crisis with phosphorus that most of the world is unaware of. Phosphorus is an essential nutrient that all living organisms need, and humans obtain this essential nutrient through phosphate found in food. To grow enough food to feed the world, the agriculture industry relies on chemical fertilizers containing phosphate from mined phosphate rock. However, modern-day farming practices that the world has become dependent on are causing a plethora of environmental, social, and economic problems due to the unsustainable practices and management of phosphorus. There have been calls for phosphorus sustainability education by organizations and reports to assist in achieving a more phosphorus-sustainable world; however, few educational materials and guidelines exist for educators. There is also a lack of awareness of this issue among the education community. This dissertation presents two studies that serve the purpose of laying a foundation for phosphorus sustainability education that educators can use to teach audiences.

The first study used the Delphi survey method to develop a consensus definition of phosphorus sustainability and a list of key concepts that are important for understanding it for educational purposes (e.g., developing curricula, lessons, assessment tools, and curricular coherence). Forty-nine science, engineering, social science, and/or policy researchers who study phosphorus sustainability were recruited for the study. These experts were able to provide their professional opinions through three iterative survey rounds, which concluded with 32 researchers agreeing on four big ideas (*circulating phosphorus*, *environmental pollution mitigation*, *healthy ecosystems*, and *sustaining and improving food production)* that should be included when defining phosphorus sustainability and four key concepts (e*nvironmental factors of phosphorus*,

food systems, *phosphorus in agriculture*, and *recovery and recycling of phosphorus*) that are important for understanding phosphorus sustainability. A fourth round was also conducted to capture the expert panels' opinions on what education levels each of the four key concepts should be taught in.

The second study utilized a semi-structured interview to capture the perspectives and strategies to teach phosphorus sustainability. Twenty researchers who study phosphorus sustainability participated in the study. Qualitative coding and thematic analysis provided perspectives on what skills, topics, and pedagogical strategies could be beneficial for audiences when learning about phosphorus sustainability. The findings included suggesting that educators use caution when framing their message to avoid excluding audiences and polarizing individual attitudes and behaviors. Participants also recommend approaching phosphorus sustainability through an interdisciplinary perspective and engaging audiences in systems thinking and experiential learning opportunities. Participants were also able to express challenges that educators and learners might endure with the topic. Recommendations are provided to assist with overcoming these potential challenges.

The Wicked Challenge of Phosphorus Sustainability: Using Education to Disrupt the Status Quo

by
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DEDICATION

To all the exemplary teachers and professors who nurtured me into the academic I am today and inspired me to pursue a career in education.

BIOGRAPHY

Julianna Nieuwsma was born in Richmond, Virginia, and raised in Matthews, North Carolina, and the Greater Charlotte area. Julianna's passion for science and nature started early in life. She spent most of her childhood outside, playing and exploring the woods and creek surrounding the double cul de sac she grew up on. In fourth grade, Hurricane Isabel and an English Language Arts project for the book *The Cay* sparked a passion for weather and hurricanes in Julianna, furthering her love of science and, at one point in time, had her strongly considering pursuing a career in meteorology. Julianna started competitive gymnastics when she was seven and continued with the sport through her senior year in high school. Balancing her gymnastics training with school and marching band prepared Julianna with the determination, self-confidence, and perseverance needed to complete a doctoral program.

She attended NC State University for her undergraduate studies, where she earned a Bachelor of Science in Zoology and minors in Genetics and Environmental Science with the intention to attend vet school one day and become a veterinarian. As an undergraduate student, Julianna was an active member of the NC State Community. She was a member of NC State's marching band, the Power Sound of the South, and the university Pep Band as a piccolo player for four years. She was also a Resident Advisor for one of the residence halls on campus for three years. Upon graduating, Julianna continued her studies at NC State and enrolled in the Master of Zoology program.

As a master's student, Julianna was a biology TA for the introductory biology courses. Upon completing her first semester as a teaching assistant and finishing a course on free-choice learning, Julianna had a newfound love for education. This love and passion for teaching persuaded her to switch her career goals from veterinary medicine to education. Since then,

Julianna has gained a variety of non-formal teaching experiences through her time interning and later working at the North Carolina Natural Science Museum and the North Carolina Zoo. By the end of her master's program, Julianna knew she wanted to pursue a career in academia to follow her passion for science education and the opportunity to mentor and inspire the next generation of science students.

In the fall of 2019, she enrolled in her Ph.D. program to complete her third and final degree from NC State to become a science education researcher and biology professor. She has worked for Dr. Gail Jones' Innovation in STEM Education Research lab at the Friday Institute, where she assisted on various research projects and gained a passion for research. Julianna joined the Science Technology Engineering Phosphorus Sustainability (STEPS) Center on campus through her work with Dr. Gail Jones. Julianna's involvement with the STEPS center inspired her to conduct her dissertation on phosphorus sustainability education. Upon graduating, Julianna is excited to continue in the world of higher education and apply the knowledge and skills she gained during her doctoral program to become an active member of the science education academic community.

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When you start a Ph.D. program, you know it will be a long, grueling, and challenging couple of years filled with rewarding highs and stressful lows; however, nothing can truly prepare you to grasp the magnitude of this arduous journey until you are already in the midst of it. I could not have gotten to this point in my doctoral degree without the vast support system I am blessed to have. Foremost, I want to thank my incredible partner, Durham, for all the love and unwavering moral and physical support he has given me. You witnessed more than anyone the emotional and physical toll this journey can impose. This last year would not have been possible without you by my side. Thank you for ensuring I always had food, seltzers, and caffeine readily available and for tolerating my excessive listening to Taylor Swift.

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Refvem, Kieren Rende Mendoza, Kat Bordewieck, Kimberly Ideus, Maddie Stallard, and Madeline Hinckle. I am so appreciative of all the laughter, memories, support, and venting we have shared. I would also like to thank my cohort. I am so lucky to have started this program with you all and will always cherish our friendship, group chat conversations, and meme sharing.

To my loving parents and sisters, who have been my number one supporters throughout my life and always believed in me, I cannot thank you enough for all that you have done for me. Next up is my amazing group of friends who have been the best cheerleaders over the years. Quality time with you all was always a breath of fresh air and the perfect escape from school stress. I extend a giant bear hug to my loving Bernese Mountain dog, Boone. You provided my days with many sweet moments over the last two years. Lastly, to the best golden in the world, Gracie, who has been by my side for every late-night writing session, providing much-needed cuddles and ensuring I took mental breaks throughout the day through fetch, walks, and trips to the dog park.

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CHAPTER 1: Introduction

In November 2022, the world's population reached eight billion (O'Sullivan, 2023). This population milestone was primarily influenced by the "Green Revolution," a period of vast technological advances in agriculture that allowed the human population to grow exponentially (Jacobs et al., 2017). One technological advancement during this time was the development of phosphorus-rich chemical fertilizers (Ashley et al., 2011). Phosphorus is an essential nutrient for all living things, making it a limiting nutrient in agricultural environments (Ågren et al., 2012). Early agricultural practices relied on organic fertilizers (e.g., manure, compost, bone meal) to grow crops; however, soil degradation and famines created a need for technological advances to obtain alternative sources of phosphorus (Russel & Williams, 1977; Schröder et al., 2010). Mining phosphate rock to chemically produce fertilizers rich in phosphorus has led to an abundance of food to sustain the human population. While phosphorus is an essential nutrient in ecosystems, anthropogenic impacts (e.g., mining, agricultural practices, waste systems) to the natural geochemical circulation of phosphorus have led to an excess amount of this nutrient in soils and aquatic environments (Yuan et al., 2018).

Surface waters worldwide are being polluted by point (e.g., industrial factories, wastewater treatment facilities) and non-point (e.g., agriculture and city runoff) sources of phosphorus. For example, it is estimated that only 20% of the phosphorus used for growing crops ends up in food; the remaining 80% is washed away in runoff or trapped in the soil. (Childers et al., 2011; Cordell et al., 2009). This overabundance of phosphorus in aquatic environments triggers costly eutrophication events (Jacobs et al., 2017). Excessive algae growth fueled by the abundance of phosphorus depletes water oxygen levels and releases toxic compounds, leading to fish kills, biodiversity loss, and human health risks (Jacobs et al., 2017; Liu & Klaiber, 2023;

Scherer & Pfister, 2016). Additionally, tourism, fishing industries, food security, recreational activities, and local economies have been negatively impacted by eutrophication (Sanseverino et al., 2016).

While phosphorus is the eleventh most abundant element in Earth's crust (Cordell & White, 2011), only phosphate, a derivative of phosphorus composed of phosphorus and oxygen atoms, is biologically available for sustaining life (Elser, 2012; Jones et al., 2020). Chemical fertilizer manufacturers supply their phosphate needs by mining phosphate rock deposits developed from decayed organic matter millions of years ago (Filippelli, 2011). The geological time scale of these phosphate rock deposits makes phosphate a finite resource (Cordell & White, 2014). There are no known artificial substitutions for phosphorus (Childers et al., 2011), and the world's current consumption rate of phosphate rock deposits is depleting global reserves (Jones et al., 2020). As these reserves diminish, food production costs will rise, threatening food security for the human population (Cordell & White, 2014). Rising costs will escalate geopolitical and inequity challenges as the demand for phosphate continues to rise (Cordell & White, 2011; Langhans et al., 2022). There is an urgent need to transform current human consumption, practices, and management of phosphorus into a more sustainable system.

Phosphorus sustainability has been referred to as a wicked problem, a complex sociocultural problem that is difficult to solve (e.g., Jones et al., 2020, Stamm et al., 2022). Improving the sustainability of phosphorus will be a complex challenge requiring social, economic, and environmental changes and innovations. As a wicked problem, phosphorus sustainability will require the cooperation of stakeholders and researchers from a range of disciplines (McWilliam et al., 2008). The interconnectedness with other wicked problems, such

as climate change, will escalate the environmental ramifications of phosphorus-driven eutrophication events (Rodgers, 2021; Sinha et al., 2017).

Statement of the Problem

Over the last several decades, researchers worldwide have studied phosphorus sustainability challenges and explored solutions to improve system efficiency and reduce environmental harm (e.g., Haygarth et al., 2014; Metson et al., 2015; Stamm et al., 2022; Weeks & Hettiarachchi, 2019). Multiple phosphorus sustainability organizations and published reports have addressed the need for phosphorus sustainability education. For example, the Science and Technologies for Phosphorus Sustainability (STEPS) Center identified education as one of nine stakeholder groups that could assist with reducing humanity's mined phosphate consumption rate and reduce the amount of phosphorus lost to the environment (*Roadmap Toward Phosphorus Sustainability*, 2023). The *Our Phosphorus Future* report (Brownlie et al., 2022) mentions education several times throughout the report as playing an essential role in raising awareness around phosphorus recycling, the impact of diet choices on phosphorus footprints, and phosphorus waste reduction.

Public awareness plays a critical role in sustainable development goals. Educating the general public on sustainable development goals strengthens the public's participation and commitment to implementing sustainable policies and programs (Odoom et al., 2024). Today's students comprise a key demographic group of the general public and will be vital in developing and implementing technological advances and sustainable practices. Research states that education can have lasting impacts on shaping students' mentalities for 50 to 60 years (Chickering & Bowen, 1979) and affect society for centuries (Žalėnienė & Pereira, 2021). For

example, educating students on climate change can increase climate change concerns among students' parents (Lawson et al., 2019).

Providing educational opportunities for students and the rest of the general public to learn about phosphorus has the potential to raise awareness and assist with implementing effective change toward phosphorus sustainability. Despite the growing prominence of sustainable development education among all levels of education (e.g., preK-higher education; Žalėnienė & Pereira, 2021), phosphorus sustainability has not been frequently addressed. There is currently little guidance and educational materials available to the education community regarding phosphorus sustainability education. Literature searches across multiple databases (e.g., Web of Science, ERIC, Google Scholar) have unearthed only a handful of practitioner articles addressing phosphorus sustainability classroom lessons (Oerther et al., 2006; Seibert et al., 2020; Zowada et al., 2020). In order to provide effective phosphorus sustainability education, the education community (e.g., educators and education researchers) needs to be knowledgeable on the subject, pedagogical strategies for teaching it, and the challenges they may encounter when teaching it.

Unlike other sustainability challenges, wicked problems (e.g., climate change, energy, ozone depletion), phosphorus has been left out of education standards and curricula. For example, the *Next Generation Science Standards* (NGSS) addresses the following essential elements: carbon, oxygen, hydrogen, and nitrogen; however, it never mentions phosphorus (National Research Council Lead States, 2013). NGSS does include standards on biogeochemical cycles; however, emphasis is only placed on the circular flow of carbon. This is an issue, especially at the primary and secondary levels of education, because high-stakes testing has led teachers to focus education lessons only on what their students will be tested on (Madaus & Russell, 2010; Saaticioglu et al., 2021). Studies show that one of the side effects of high-stakes

testing is curricula narrowing (e.g., Berliner, 2014; Saaticioglu et al., 2021; Madaus & Russell, 2010), so if phosphorus is not included in content standards and curricula, it is unlikely that educators will incorporate phosphorus lessons into their classrooms.

Phosphorus sustainability also lacks a formal definition, key concepts, and curricular coherence. Sustainability terms are often poorly defined (Glavič & Lukman, 2007; Salas-Zapata & Ortiz-Muñoz, 2019; Urdan & Luoma, 2020), leading to poor communication and misunderstandings between teachers and students and negatively impacting sustainability educational instruction, lesson design, and student learning (Urdan & Luoma, 2020). Phosphorus sustainability also involves knowledge and input from a variety of different disciplines, all of which can attach different meanings and conceptual understandings to the term (Glavič & Lukman, 2007; Salas-Zapata & Ortiz-Muñoz, 2019; Urdan & Luoma, 2020). Because phosphorus sustainability involves many disciplinary fields, fruitful scientific discourse will require a well-defined definition (Wu & Hobbs, 2007). Key concepts will also assist with providing effective phosphorus sustainability education because concepts help develop an educator's and learner's understanding of a topic by offering opportunities to connect to other topics, review content, or put knowledge into context (Cambridge Assessment International, 2014). Developing a set of key concepts for phosphorus sustainability could assist educators with dividing this complex topic into more manageable units or provide opportunities to adapt phosphorus sustainability into lessons by connecting phosphorus sustainability to other topics that share similar key concepts. In addition, identifying key concepts could assist with developing curricular coherence. Establishing coherence across curricula can assist educators with aligning content topics and the sequencing of teaching topics to students (Fortus et al.,

2015), help improve student performance (Schmidt et al., 2005), and allow students to develop a deeper knowledge of science content (Shin et al., 2019).

Research Purpose and Significance

The purpose of this dissertation is to begin preliminary investigations on the most effective ways for educators to teach phosphorus sustainability. It will explore the key concepts and skills that are necessary for learning phosphorus sustainability and provide educational suggestions that can be used to create quality phosphorus sustainability curricula, standards, lessons, and curricular coherence. These goals will be accomplished through two separate but related studies, both of which draw upon the expertise of researchers who study phosphorus sustainability.

The first study (Chapter 2) utilizes the Delphi technique to capture the expert opinions of researchers who study phosphorus sustainability. Qualitative and quantitative analysis is used to define phosphorus sustainability, discover the critical concepts that are important for learning and understanding it, and suggest at which education levels specific concepts should be taught in. Study participants came from a variety of disciplinary fields and had prior experience researching phosphorus. Results were also analyzed to identify discrepancies between different disciplinary field experts' ratings of the importance of teaching specific key concepts. The findings from this study provide the education community with a concise and descriptive definition of phosphorus sustainability that was agreed upon by experts. The list of key concepts can inform the education community as they start developing curricula, standards, lessons, and curricular coherence.

The second study (Chapter 3) explores phosphate experts' recommendations of key features to include in education on phosphorus sustainability. This study aimed to provide the

education community with the background knowledge they need to teach phosphorus sustainability. Semi-structured interviews were conducted with researchers who study phosphorus sustainability to capture their perspectives on what skills, topics, and pedagogical strategies would benefit students and the general public based on their experience in the field. It also highlights potential challenges the experts think educators and learners may face when teaching or learning phosphorus sustainability. Discussion of the results provides recommendations on overcoming these challenges and guidance on things to consider and employ when designing and teaching phosphorus sustainability lessons.

The final chapter of this dissertation connects the two studies, providing a final discussion and conclusion. The chapter ends with recommendations for educators and areas of future research to build upon based on the analysis and discussion of these two studies.

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CHAPTER 2: Defining and conceptualizing phosphorus sustainability for educators: A Delphi study of researchers who study phosphorus sustainability

Abstract

Humans worldwide are struggling to manage dozens of wicked problems impacting the sustainability of a growing population. One of these complex problems impacting humanity is the wicked challenge of phosphorus. Phosphorus is an essential nutrient for life; however, the world's current practices for managing this critical resource have created many sustainability challenges. There is an urgent need to provide phosphorus sustainability education; however, little is known about teaching and learning this topic. Using a Delphi methodology, 49 experts in phosphorus sustainability were surveyed to develop a comprehensive consensus definition of phosphorus sustainability and identify key concepts for educators to develop curricula, lessons, assessments, and curricular coherence. Delphi participants recommended that four big ideas (*circulating phosphorus*, *environmental pollution mitigation*, *healthy ecosystems*, and *sustaining and improving food production)* define phosphorus sustainability and that educators should address four key concepts (*environmental factors of phosphorus*, *food systems*, *phosphorus in agriculture*, and *recovery and recycling of phosphorus*). Using the central ideas that emerged from this study, recommendations to educators for teaching phosphorus sustainability, future research suggestions, and implications for curricula design are discussed.

Introduction

Sustainability is a term commonly used with various meanings, applications, and interpretations (Moore et al., 2017) and is a topic of increasing importance in education (Sass et al., 2024). The World Commission on Environment and Development (WCED) defines sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (Thomsen, 2013, p. 2358). While some researchers view and apply the terms sustainability and sustainable development differently (Jeronen, 2013; Ruggerio, 2021), they are often used interchangeably and discussed in conjunction with each other in literature. There is a strong correlation between achieving sustainable development and human well-being (De Neve & Sachs, 2020). Since 1972, dozens of sustainability education initiatives have been created by global and national organizations (Burton, 1987; Mensah, 2019; Wu-Rorrer et al., 2022) as well as higher, secondary, and primary educational learning environments (Merritt et al., 2018; Žalėnienė & Pereira, 2021). One area of focus in education settings is the sustainability of natural resources. Educational lessons have focused on sustaining natural resources such as trees, water, fossil fuels, and minerals. However, a natural resource that has received little attention from the educational community is phosphorus.

Phosphorus is an essential nutrient that all living organisms require for multiple functions and is the eleventh most abundant element in Earth's crust (Cordell & White, 2011) and the thirteenth most abundant element in the universe (Elser, 2012). However, only specific forms of phosphorus (e.g., phosphate) are biologically available for sustaining life (Elser, 2012; Jones et al., 2020). Animals obtain phosphorus through their diet, and plants obtain phosphorus from the soil through their roots, making phosphorus an important nutrient for agriculture. Early

agricultural practices relied on natural deposits of inorganic phosphate (phosphate ions released into the environment from chemical weathering) or organic phosphate (phosphate incorporated into organic molecules and returned to the environment through decaying organic matter or excrement) to grow crops. However, a growing human population, famines, and soil degradation initiated technological advances and the creation of chemical fertilizers that contributed to a dramatic increase in global crop yields (Schröder et al., 2010). These manufactured chemical fertilizers obtain phosphorus from mined phosphate rock deposits formed from organic matter decay over millions of years. Using chemical fertilizers has led to an abundance of food for most of the world, allowing the human population to grow substantially over the last two centuries.

This growth and dependence on phosphates, a non-renewable resource, have contributed to a current sustainability crisis due to humanity's consumption, practices, and management of phosphorus. The world's current consumption rate of phosphate rock deposits is depleting the world's reserves (Jones et al., 2020). Phosphate rock deposits are only found in specific parts of the world (Walsh et al., 2023). Five countries (Morocco, China, United States, Egypt, Algeria, and Syria) account for approximately 85% of the world's global phosphate rock reserves, and three countries (Morocco, China, and the United States) account for two-thirds of the world production of mined phosphate rock (Jasinkski, 2021). There are no known artificial substitutions for phosphorus (Childers et al., 2011), so as these reserves begin to diminish, food security for the human population will become threatened (Cordell et al., 2009). Geopolitical and inequity challenges will increase as the demand for this finite resource continues to rise despite the decrease in supply (Walsh et al., 2023).

It is estimated that only one-fifth of mined phosphate used in fertilizers ends up in food; the rest is lost to the environment (Cordell et al., 2009). Most of this phosphorus is washed away

in agricultural runoff, polluting aquatic systems (Jacobs et al., 2017) and creating major water quality problems (Parry, 1998; Stamm et al., 2022). The increased phosphorus concentration in surface waters leads to deadly and costly eutrophication events (Jacobs et al., 2017). During these events, decreased oxygen levels and toxic compounds released from the over-growth of algae lead to fish kills, biodiversity loss, and harmful impacts on human health (Jacobs et al., 2017; Schröder et al., 2010). Researchers predict that the frequency of these eutrophic events will rise as phosphorus runoff continues to pollute surface waters (Jarvie et al., 2020). Therefore, there is a growing urgency to provide education on this wicked problem. This study investigated the fundamental knowledge and constructs associated with phosphorus sustainability in an effort to define and lay a foundation for phosphorus sustainability education.

Background Literature

Today's society faces a plethora of wicked problems that require advanced problem-solving skills, critical thinking, effective communication, and knowledge from multiple disciplines to find solutions and strategies to address these problems. Wicked problems, such as climate change and heart disease, are characterized as wicked because they are challenging to resolve due to their inherent complexity and interconnected nature with society and other sociocultural issues (Rittel & Webber, 1973). Wicked problems are difficult to define and put into categories and have ten distinguishing properties (see Table 2.1).

Table 2.1

The Ten Distinguishing Properties of a Wicked Problem

	Distinguishing Property	Explanation of property
1.	"There is no definitive formulation of a wicked problem."	The exact causes for a wicked problem in one area are different for another area.
2.	"Wicked problems have no stopping rule."	The challenge of defining what causes a wicked problem makes it hard to state when the problem has been "solved."
3.	"Solutions to wicked problems are not true-or-false but good-or-bad."	Opinions from different stakeholders mean there is no idealized end state; attention should be given to improving the situation rather than solving it.
4.	"There is no immediate and no ultimate test of a solution to a wicked problem."	Implementation of any solution will have an impact (positive or negative) over an extended period of time that will lead to other repercussions. Impacts cannot be accessed until all repercussions have occurred.
5.	"Every solution to a wicked problem is a "one-shot" operation because there is no opportunity to learn by trial-and-error; every attempt counts significantly."	A Wicked problem can't be replicated in a controlled lab environment because it is a human-caused and not natural phenomenon. Strategies to resolve the problem are tested directly in the world, and the impacts (good or bad) have long-lasting effects.
6.	"Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan."	It's hard to define all the causes of a wicked problem, making it impossible to define all the potential solutions.
7.	"Every wicked problem is essentially unique."	A solution that worked for a closely related wicked problem would not be guaranteed to work for another. Every wicked problem can have a unique factor, making it different from a previous one.
8	"Every wicked problem can be considered to be a symptom of another problem."	Wicked problems cause other wicked problems (e.g., poverty contributes to food insecurity), so addressing one wicked problem might positively or negatively impact another.
9.	"The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution."	A wicked problem always has more than one explanation for why it occurs, with the validity of the explanation depending on the stakeholder's view.

Table 2.1 (continued).

Distinguishing Property	Explanation of property
10. "The planner has no right to be wrong."	Those invested in testing solutions are responsible for any negative effects they might cause.

Note. Distinguishing properties from (Rittel & Webber, 1973, p. 161-166).

Sustainability as a Wicked Problem

Sustainability meets the criteria of a wicked problem and has been acknowledged as one among scholars (Brønn & Brønn, 2018; Pryshlakivsky & Searcy, 2013). Sustainability involves multiple stakeholders possessing different values, beliefs, and objectives (Blok et al., 2016; Brønn & Brønn, 2018), the cause of the problem is difficult to define, and the effects are uncertain and unknown (Blok et al., 2016). The complexity surrounding sustainability is derived from the competing interests of the three pillars that comprise it: social, economic, and environmental (Purvis et al., 2019). All three pillars contribute to an abundance of stakeholders who are invested in sustainable development decisions. Sustainability and sustainable development are further complicated when issues of ethics, justice, and equality are also considered (Jabareen, 2008). The wicked problem of sustainability requires scholars from different disciplines to come together to combine their discipline-specific knowledge along with the cooperation of stakeholders. Bridging multiple disciplines and stakeholders requires strong collaboration and "demands more epistemological and cultural agility" (McWilliam et al., 2008, p. 251).

The Wickedness of Phosphorus

The anthropogenic disruptions to the phosphorus cycle have created complex and open-ended challenges of food security, environmental degradation, public health, and geopolitical conflicts which characterizes it as a wicked problem. Addressing phosphorus sustainability will

require the cooperation of many stakeholder groups and disciplinary fields. It will require advancements at the atomic scale (Jones et al., 2020), applications and management practices in industry fields (Grieger et al., 2023), geopolitics and policies (Chowdhury et al., 2017), social behavior with diet choices and food waste (Brownlie et al., 2022), and waste management (Jacobs et al., 2017).

Phosphorus sustainability is interconnected with other wicked problems, a defining characteristic of a wicked problem (Rittel & Webber, 1973). For example, eutrophication events caused by excess phosphorus in surface waters contribute to climate change, and climate change contributes to eutrophication events. Algal blooms release greenhouse gases (e.g., methane, carbon dioxide, and nitrous oxide) into the atmosphere, contributing to global warming and changes in weather patterns (e.g., more intense rainstorms; Beaulieu et al., 2019). Earth's rising temperatures increase the temperature of surface waters and the frequency of storms, contributing to pollution runoff (Glibert, 2020; Nazari Sharabian et al., 2018). The increased temperatures and extreme weather events from climate change and the higher concentration of phosphorus from runoff in surface waters provide the conditions needed for a eutrophic event, making algal blooms more likely to occur (Glibert, 2020). Like other wicked problems, phosphorus sustainability is interconnected with potable water security, biodiversity loss, food security, and poverty (El Wali et al., 2021).

Another characteristic of phosphorus sustainability is that the challenges and causes associated with phosphorus are different depending on the part of the world. The issues and solutions for the Global North, where phosphorus is overly abundant in the environment due to the over-application of fertilizers, differ greatly from the Global South, where phosphorus is scarce or inaccessible due to soil degradation and limited accessibility to phosphorus-rich

fertilizers (Brownlie et al., 2022; Cordell & White, 2014). These contrasting causes and needs are referred to as the phosphorus paradox (Lougheed, 2011) and impact community health differently. People in the Global South will likely be among the first to experience food insecurity due to the rising costs of fertilizers and geopolitical conflicts (Cordell et al., 2009). People in the Global North have a heightened risk of losing access to safe drinking water due to eutrophic events in water sources (Brownlie et al., 2022; Dodds et al., 2009). Excessive phosphorus runoff has also negatively affected tourism, fishing industries, food security, human health, and local economies (Häder et al., 2020; Newton et al., 2020).

Rittel and Webber (1973) described all wicked problems as being essentially unique from each other. Unlike climate change and sustainable energy, where efforts to address energy needs involve using alternative energy sources (e.g., choosing renewable energy sources over fossil fuels), there are no alternative sources of phosphorus.

Study Context

Scholars have identified education as one of the key strategies for addressing the wicked problem of phosphorus sustainability (Brownlie et al., 2022; Jacobs et al., 2017; Stamm et al., 2022). Education has been shown to raise awareness of environmental issues (Hadzigeorgiou & Skoumios, 2013; Ma'rufah et al., 2021); however, very little educational guidance and information is available to educators to teach phosphorus sustainability. Unlike other wicked problems (e.g., climate change, sustainable energy), this area has not been extensively studied from an educational lens. Only a few practitioner studies have reported on phosphorus-related instruction (e.g., Oerther et al., 2006; Seibert et al., 2020; Zowada et al., 2020). In order to provide quality educational instruction on phosphorus sustainability, educators will need to know how this topic is defined and the critical concepts that should be addressed.

Ambiguous or ill-defined scientific language can hinder learning. Studies have shown that when students lack definition clarity about sustainability, it can negatively impact their learning and performance on assignments (e.g., Urdan & Luoma, 2020). One of the challenges in teaching phosphorus sustainability is that it requires knowledge from multiple disciplines (Redman, 2013). Different disciplines can attach different meanings to the same word, making interdisciplinary conversations difficult (Pellmar & Eisenberg, 2000). The field of sustainability, in particular, has terminology that is frequently used and defined differently by authors and organizations (Glavič & Lukman, 2007; Salas-Zapata & Ortiz-Muñoz, 2019; Urdan & Luoma, 2020). Effective sustainability education requires an unambiguous common language that can be shared among disciplines.

Current phosphorus sustainability research lacks a consistent definition that is used among different disciplines. Instead, phosphorus sustainability tends to be described indirectly by defining what the element phosphorus is and its role in different systems (e.g., waste, food, biological). Phosphorus sustainability is often discussed in literature in conjunction with reducing environmental pollution; however, as a finite resource, it has economic and sociopolitical components and applications, such as global food security (Schröder et al., 2010). If educators are to teach phosphorus sustainability, there needs to be a clear and inclusive definition that encompasses all the different perspectives and interconnected factors of sustainability available for them to use.

In addition, educators need to be aware of the key concepts that are important for learning and understanding phosphorus sustainability. Key concepts have been delineated for a variety of science topics, such as nanoscience (Ha & Lajium, 2022) and climate change (Jarrett, et al.,

2011). Identifying key concepts facilitates linking one topic to another and putting knowledge into context (Cambridge Assessment International, 2014).

Defining and conceptualizing phosphorus sustainability has the potential to assist with developing coherence across curricula, instruction, and assessment in educational environments. Curricular coherence is the alignment of content topics, the depth they are taught, and the sequencing of topics within and across grade levels (Fortus et al., 2015). A coherent curriculum will be important for phosphorus sustainability education because it has been documented to assist students in developing a deeper knowledge of core science ideas (Shin et al., 2019). Additionally, student performance improves when students learn using a coherent curriculum (Schmidt et al., 2005).

As educators begin to frame phosphorus sustainability education, having access to domain experts' knowledge can be valuable in developing educational materials on phosphorus sustainability. Research has documented the benefits of expert knowledge. Research has shown experts can identify relevant information more efficiently than novices (Bruning et al., 2011; De Groot, 1978). Additionally, experts are more proficient at organizing information than novices (Bruning et al., 2011); therefore, experts can be a valuable resource to the education community when attempting to conceptualize and incorporate a new topic into education.

To assist the education community in raising awareness of the wicked problem of phosphorus sustainability, this study utilized the Delphi technique to document the knowledge and expertise of scholars who study phosphorus sustainability to define phosphorus sustainability and to develop a list of key concepts. The following research questions guided this Delphi study:

1. How do researchers who study phosphorus sustainability define phosphorus sustainability?

2. What are the critical concepts that should be taught in order to understand phosphorus sustainability?
3. How do agreement ratings for researchers from different disciplines differ when conceptualizing phosphorus sustainability?
4. Which sustainability concepts should be taught at different educational levels (primary, secondary, undergraduate, and graduate)?

Delphi Methods

Delphi studies (Gupta & Clarke, 1996; Habibi et al., 2014) have been used to define and characterize various topics. This research method involves bringing together a panel of experts on a specific topic to develop or identify a central set of ideas (Ruppert & Duncan, 2017). It has been described as a qualitative approach for finding quantitative results (Ng, 2018). Four characteristics consistent among Delphi studies, which are different from other group decision-making research methods, are anonymity, iteration with controlled feedback, group response, and expert input (Windle, 2004). Delphi studies have previously used expert opinions to develop definitions for science topics or reveal essential concepts of various STEM (science, technology, engineering, mathematics) topics that are important to be taught in educational settings. For example, a Delphi study involving nanotechnology researchers and science educators identified eight essential concepts related to nanoscale science and technology that should be taught in high school (Sakhnini & Blonder, 2015).

Developing or identifying a central set of ideas occurs by engaging Delphi participants in an iterative survey paired with controlled feedback until a statistical consensus or stability in the expert community is achieved (Osborne et al., 2003). The number of rounds included in a Delphi study varies and is carefully determined based on criteria set out by the researchers. Delphi

studies are bounded by the amount of time available to complete the study, how many questions are being asked to be addressed by the participants, survey fatigue from participants, and group consensus and stability of items (Hasson et al., 2000; von der Gracht, 2012). The original Delphi technique included four rounds (Hasson et al., 2000); however, two to three-round Delphi studies have become more common. A systematic review of Delphi studies found thirteen studies with two rounds, sixteen with three rounds, and only two with four rounds (Gargon et al., 2019).

During the first round of a Delphi study, expert panelists provide detailed written responses to open-ended questions on the targeted topic. Participants' responses are analyzed to identify central themes or "big ideas," which are shared with participants during the second round of data collection. During this second round, participants use Likert responses to indicate their level of agreement towards the themes or "big ideas" generated from the first round and provide a detailed explanation of their agreement ratings. The survey about the big ideas is modified based on the collective responses generated during the previous round before being shared for the next round. Modifications might include the renaming or rephrasing of survey items or removing items that received low group average ratings (Osborne et al., 2003; Ruppert & Duncan, 2017). This interactive survey cycle continues for studies until the pre-determined amount of rounds has occurred or participant alignment of key ideas is achieved. An important component of this iterative cycle is achieving group consensus and stability on survey item ratings from the panel.

Group consensus is achieved when individual evaluations gather around a median response with minimal divergence, and stability is reached when there is little, if any, shift in positions (Brooks, 1979). Examples of statistical measurements to calculate consensus and/or stability include, but are not limited to, a certain percent level of agreement, average percent of

majority of opinions, mode/mean/median ratings and standard deviations, interquartile range, coefficient of variation, Chi-square test for independence, McNemar change test, and Wilcoxon matched-pairs signed-ranks tests (von der Gracht, 2012). Research has shown that providing feedback (e.g., informing groups of the average agreement score from a previous round) impacts participants' responses and level of consensus (Barrios et al., 2021). Sociodemographics (e.g., age, gender, education) have not significantly impacted panel consensus in previous studies (e.g., Barrios et al., 2021; Makkonen et al., 2016). Group consensus has been shown to differ between members of a Delphi panel who belong to interest groups associated with a topic and panelists who belong to other expertise groups (e.g., administration, non-governmental organizations, or research; Makkonen et al., 2016).

Panelist group size ranges vary across Delphi studies, with most having between 10 to 50 experts (Shariff, 2015). A Delphi study would not typically have below 10 participants because it does not generate enough ideas, and they usually do not exceed 50 participants due to cost inefficiencies related to time, products, and the iteration process (Needham & de Loë, 1990). Large number of participants can also increase participants' attrition rates (Gargon et al., 2019). Research has found little improvement to Delphi results (e.g., addition of new ideas, reduction in error, or increased reliability or results) once the panel size exceeds 30 members (Brooks, 1979).

One benefit of a Delphi study is that, unlike a single survey, interview, or focus group, the Delphi method allows participants to reflect on their responses in light of the other participants' views (Barrett & Heale, 2020). Another strength of the Delphi study is the anonymity and self-pace Delphi studies provide to participants. In focus groups or in-person panels, participants' opinions may be influenced or biased by other participants' responses; however, in a Delphi study, participants can provide their responses confidentially and on their

own time (Nworie, 2011). The Delphi method also allows for the recruitment of participants from geographically diverse areas (Shang, 2023). The high dropout rate of participants throughout the study is a weakness of the Delphi technique. Attrition of panelists is expected between rounds (Gargon et al., 2019; Osborne et al., 2003). Risk factors for attrition rates often increase with each additional round that is included as part of the study (Shang, 2023), large panels, and studies with a high number of items included (Gargon et al., 2019). Researchers need to consider these risk factors when designing their Delphi study to reduce attrition rates. Another weakness of the Delphi technique is the lack of consistency among consensus measurements (von der Gracht, 2012). Despite these weaknesses, which can be mitigated or avoided with careful attention to study design and analysis, Delphi studies can be an effective tool to document experts' ideas on a specific topic and establish which topics and perspectives experts hold in common.

Methodology

This study used a Delphi methodology to document expert perspectives on the key concepts that are important for understanding phosphorus sustainability and to develop a consensus definition of the term. This Delphi study consisted of four iterative rounds (see Figure 2.1), and the following sections provide a detailed description of 1) the expert panel, 2) the data collection and analysis procedures for each round, and 3) the validity of results and consensus of responses.

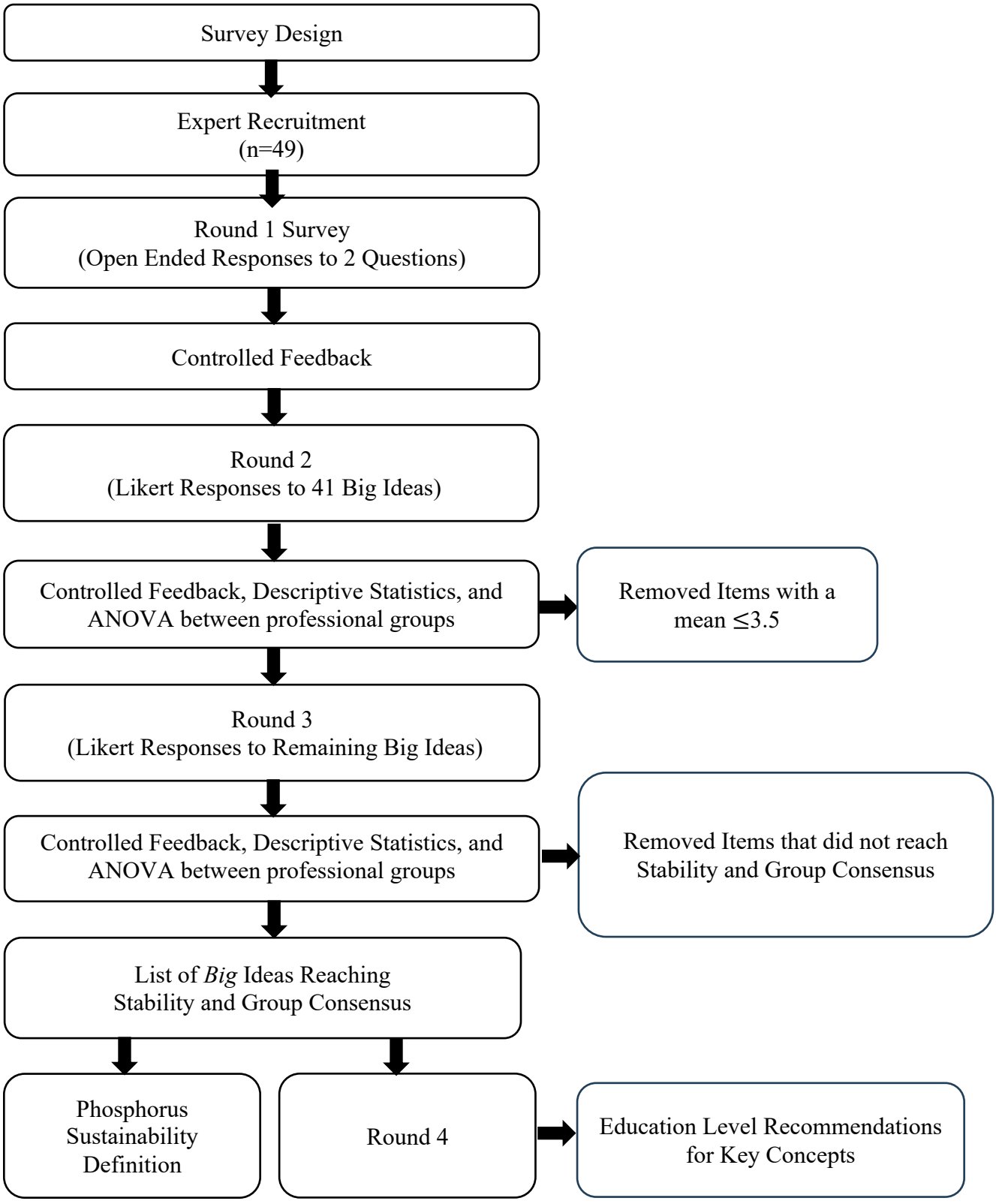
Participants

For this study, experts in phosphorus sustainability were defined as individuals with acknowledged expertise in communicating or researching components of phosphorus sustainability. The expert panel consisted of researchers who have either published or are

actively conducting research on phosphorus sustainability or are members of a phosphorus sustainability research organization (e.g., The Sustainable Phosphorus Alliance [SPA]). Panelists included researchers who study phosphorus sustainability from a variety of different disciplines and scales: the materials scale (e.g., materials science, chemistry), the human-technology scale (e.g., environmental engineering, crop, and soil sciences), and the regional and global scale (e.g., economics, policy, ecology).

Figure 2.1

Flow Chart of Delphi Methodology



The targeted participants were recruited from three professional groups: 1) science, 2) engineering, and 3) social sciences/public policy. Following the recommended range guidelines of 10-50 experts for a Delphi panel (Shariff, 2015) and having 5-10 participants per group when utilizing experts from different disciplines (de Villiers et al., 2005), the study initially recruited 49 participants (see Table 2.2 for background demographics). Participants were invited through an email invitation and recruited from the membership list of phosphorus sustainability organizations (e.g., The Science and Technologies for Phosphorus Sustainability [STEPS]), authors from published phosphorus sustainability journal articles and reports (e.g., Our Phosphorus Future Report), and snowball sampling (Creswell & Poth, 2017; Habibi et al., 2014). Purposeful sampling was used to select participants from each of the three professional groups. Some participants held expertise in more than one disciplinary field and were included as members of multiple professional groups. Thirty-one people had expertise in science disciplines (e.g., limnology, chemistry, soil science), sixteen people had expertise in engineering disciplines (e.g., material science, environmental engineering, biological engineering), and fourteen people had expertise in social science or policy related fields (e.g., economics, law, public administration; see Table 2.3). Participants, on average, had 6-10 years of experience working in phosphorus sustainability.

Table 2.2

*Panelists' Demographics (*N = *49)*

Demographic	n	%
Gender		
Man	24	49
Woman	24	49
Prefer not to disclose	1	2
Ethnicity [a]		
Asian	2	4
Black or African American	1	2
Hispanic, Latinx, or Spanish	2	4
Middle Eastern or North African	1	2
White	44	90
Prefer Not to Disclose	1	1
Age (in years)		
31-40	13	27
41-50	20	41
51-60	7	14
61-70	6	12
Prefer Not to Disclose	3	6

[a] Total sample adds over 100% because two participants identified as mixed (one person identified as Hispanic/Latinx/Spanish and White, one as Middle Eastern/North African and White).

Table 2.3

*Panelists' Expertise and Years of Experience (*N = *49)*

Expertise and Years of Experience	n	%
Professional Group [a]		
Engineering	16	33
Science	31	63
Social Sciences and Public Policy	14	29
Years of Experience in Primary Disciplinary Fields of Expertise		
6-10	9	18
11-15	12	25
16-20	10	20
More than 20	18	37
Years of Experience in Additional Disciplinary Fields of Expertise [b]		
3-5	3	6
6-10	5	10
11-15	6	12
16-20	4	8
More than 20	8	16
Years of Experience Studying Phosphorus Sustainability		
1-2	4	8
3-5	12	25
6-10	14	29
11-15	8	16
16-20	4	8
More than 20	7	14

[a] Total sample adds up to over 100% because 27 participants reported having an additional disciplinary field of expertise, so some participants are included in two professional groups.

[b] Only 27 participants reported having an additional disciplinary field of expertise, so the total does not add up to 100%. One participant reported having an additional disciplinary field but did not report how many years of experience they had, so results are shown for only 26 participants.

Data Collection and Analysis

Round 1

The first round of the study was an open-ended brainstorming session that began by sending participants a Qualtrics survey via email. Before launching the first round, the open-ended questions were reviewed by a panel of two science education researchers and were piloted with two postdoctoral scholars researching phosphorus sustainability. Questions were revised for clarity based on feedback provided by the review panel and postdoctoral scholars. Perspectives regarding the essential ideas of phosphorus sustainability were sought through participants' responses to the following open-ended questions:

1) *In your own words, how should phosphorus sustainability be defined?*

2) *What key concepts and skills should be taught in order to understand phosphorus sustainability? For each concept and skill you provide, give a clear description of the concept or skill and elaborate on why knowledge of that concept or skill would be important for a person to understand phosphorus sustainability.*

Responses were analyzed using open coding to generate a list of items for the panel to rate in the second round of the study. A constant comparative method was used to analyze all the responses multiple times to identify and clarify data themes and descriptions that would comprise the codebook (Creswell & Poth, 2017). Three science education researchers reviewed the codebook (see Appendix A), and minor revisions were made based on feedback. Two science education researchers coded twenty percent of the responses to obtain inter-rater reliability. Inter-rater reliability was calculated using Kappa's coefficient, with the researchers obtaining a final average rating of .90 across all the codes, which is considered a very good or excellent rater agreement (Xie, 2011). The primary researcher finished coding the remaining survey responses.

Coded responses were then used to generate survey items referred to as “big ideas” for the round two questionnaire. Each “big idea” was accompanied by a brief one to two-sentence description of the idea and a list of supporting statements developed from the participant’s responses. Figure 2.2 provides an example of a big idea survey item presented in the survey.

Figure 2.2

Example of Survey Item Format

Big Idea: Environmental Pollution Mitigation
Summary
When defining phosphorus sustainability, it should include preventing or reducing excess amounts of phosphorus from entering the environment (e.g., waterways, aquatic environments, soil) and polluting the environment above homeostatic phosphorus levels.

Exemplary Supporting statements
1) Minimizing excess phosphorus transfer from land to waterways.
2) Responsible management of phosphorus without degrading our soil and water systems.
3) The efficient use and extraction of global phosphorus reserves in a way that limits environmental impacts across the phosphorus life cycle.

Round 2

During the second round, participants received a second Qualtrics survey via email containing 41 items generated from the first round (see Appendix B). Items were randomized in the survey to reduce question order effects among participants and improve reliability (Thau et al., 2021). Participants were asked to rate each item’s importance in relation to two questions:

1) *How important is it to include this idea when defining phosphorus sustainability?*

2) *How important is teaching this idea in order to understand phosphorus sustainability?*

Participants rated items using a five-point Likert scale ranging from 1) “not important” to 5) “extremely important.” In addition, participants were allowed to provide feedback on each big idea, its summary statement, supporting statements, or justification for the rating they provided.

Quantitative data analysis of round 2 responses used participants' Likert ratings to calculate each item's mean and standard deviation. Items were considered to be very important or extremely important by the panel when an item's mean was greater than or equal to four. A high level of group consensus occurred when standard deviations were less than one. Participants' written feedback for each item's title, summary, and supporting statements were evaluated, and revisions were made according to the experts' comments.

Round 3

The third round, containing the updated version of the previous survey (see Appendix C), was sent to participants. The updated survey only included the most highly rated items from round 2 to maintain the quality of survey responses and reduce survey fatigue. Research on the Delphi method has reported that responses to questions toward the end of the questionnaire tend to be less robust and informative when participants participate in lengthy and detailed questionnaires (Judd, 1971). Including only the most highly rated items in the third round is a standard protocol in Delphi studies (e.g., observed in Osborne et al., 2003; Ruppert & Duncan, 2017). Items that received a mean rating greater than or equal to 3.5 were included in the third iteration of the study. Items once again were randomly arranged for each participant. Participants were asked to rate each item again in relation to the two questions used in round 2 and provide constructive feedback.

As was done in the previous round, descriptive statistics were calculated for each item. This study followed the mean cutoffs used in prior studies (e.g., Osborne et al., 2003) to determine expert consensus for the big ideas. Study consensus was defined as two-thirds (66%) of experts rating the big idea with a four ("very important") or higher. Stability was determined using a Spearman Rank Correlation test (Kalaian & Kasim, 2012; von der Gracht, 2012).

Stability was determined when the correlation between the average ratings from the experts for items between rounds was statistically significant, meaning the average group rating for an item was not statistically different between rounds 2 and 3. Items where the group average between rounds was too different, would not have a statistically significant Spearman correlation value and would not be considered to have group stability. A final definition of phosphorus sustainability was identified using the experts' survey responses. In addition, a list of the key concepts for understanding phosphorus sustainability was generated based on experts' responses. Only items that achieved stability and consensus were included in the phosphorus sustainability definition or list of key concepts.

Additional Analysis

In addition to the previous statistical analyses, the mean degree of variation of responses for the three professional groups (science, engineering, social science/policy) was analyzed with a one-way analysis of variance (ANOVA) statistical test using SPSS 29. Because some participants had expertise in more than one of the professional groups, the ANOVA contained a fourth group (interdisciplinary) in addition to the other three professional groups. ANOVAs were conducted for both the second and third rounds.

Round 4

Round four utilized items that reached panel consensus and stability. The survey asked participants to select which stage of academic development (e.g., primary education, secondary education, undergraduate education, or graduate education) each of the big ideas of phosphorus sustainability should be taught. Participants were allowed to select more than one education level for each item. Descriptive statistics (e.g., frequency) were calculated for each education level for each item.

Results

Table 2.4 provides a summary of key findings for each round of the study.

Round 1

Forty-nine phosphorus sustainability scholars responded to the first round's two open-ended questions. Responses to the first open-ended question (*In your own words, how should phosphorus sustainability be defined?*) were separated into 126 components. On average, each person's definition of phosphorus sustainability contained 2.57 components. For example, Participant 12 defined phosphorus sustainability as "To have as little reliance on mined phosphorus as possible while meeting ecosystem health and food production goals." This response was broken down into three components: 1) little reliance on mined phosphorus, 2) meeting ecosystem health goals, and 3) meeting food production goals. For the second open-ended question (*What key concepts and skills should be taught in order to understand phosphorus sustainability?*), the expert panel suggested 212 concepts.

Each participant, on average, recommended 4.32 concepts as important to include in one's teaching for the learner to understand phosphorus sustainability. For example, Participant 39 believed three concepts were important: 1) "Understanding the finite nature of phosphorus to avoid its depletion and address potential conflicts over its appropriation," 2) "Understanding the multiple and significant uses of phosphorus (e.g., food security)," and 3) "Understanding social, economic, and environmental impacts connected with the use of phosphorus to develop model governance aiming at promoting a sustainable use of phosphorus."

Coding and thematic analysis of responses to the open-ended questions resulted in ten themes, referred to as "big ideas" for defining phosphorus sustainability, and thirty-one themes

for learning phosphorus sustainability. Table 2.5 provides a complete list of the *definitional* and *key concept* big ideas.

Round 2

Thirty-seven out of the original forty-nine participants continued with the second round of the study, and the attrition rate between the first two rounds was 24.49%. Table 2.6 (*definitional* big ideas) and Table 2.7 (*key concept* big ideas) report the means and standard deviations for participants' importance ratings for each of the forty-one big ideas generated from the first round. Participants provided a variety of constructive feedback to improve the big idea titles, summary descriptions, and exemplary statements. For example, three out of the five exemplary statements for the *definitional* big idea *decrease dependency on mined phosphate* were excluded from the third round of the survey, and the other two statements were emended based on suggestions by several participants (see Figure 2.3). Participant suggestions to remove three of the exemplary statements included comments such as “this big idea is important, but exemplary supporting statement number 3 is not relevant to it” (Participant 37), “I do not agree with statement number 3” (Participant 11), and “I’d eliminate #5, newly mined phosphates are critical for the electric car industry’s development” (Participant 1). The second exemplary statement was edited to include the suggestion provided by Participant 35, “this big idea would be rated extremely important if it included concepts related to monopoly, geopolitical insecurity, and world prices that make reliance on imported mined P a vulnerability for most regional and national food systems.” Participants also shared when they liked specific exemplary statements. As seen in Participant 38’s comment on the big idea of *environmental pollution mitigation*, “Quite like this one: #4 ‘Responsible management of phosphorus without degrading our soil and water systems.’”

Table 2.4

Summary of Study Results for Each Survey Round

Survey Round	Number of Participants (n)	Task	Summary of Key Findings
Round 1	49	Open-ended responses to: *In your own words, how should phosphorus sustainability be defined?*	10 *Definitional* big ideas.
		Open-ended responses to: *What key concepts and skill should be taught in order to understand phosphorus sustainability?*	28 *Key concept* big ideas.
Round 2	37	Likert Ratings for each of the forty-one big ideas generated from round 1 responses.	13 Big ideas removed from the survey after data analysis based on participant feedback (e.g., mean < 3.5, written feedback).
Round 3	34	Likert Ratings for each of the remaining 28 big ideas from round 2.	4 *Definitional* big ideas reached stability and group consensus. (*environmental pollution mitigation, circulating phosphorus, healthy ecosystems, sustaining and improving food production*) Definition of phosphorus sustainability conceptualized from 4 *definitional* big ideas.

Table 2.4 (continued).

Survey Round	Number of Participants (n)	Task	Summary of Key Findings
			4 *Key concept* big ideas reached stability and group consensus (*environmental factors of phosphorus, food systems, phosphorus in agriculture, recovery and recycling of phosphorus*)
			ANOVA/Post-hoc Tukey's Test revealed significant difference between disciplinary groups means for four big ideas. (*circulating phosphorus, geopolitics, mass balances, systems thinking*).
Round 4	32	Expert panelists indicated which education levels they would teach each of the key concept big ideas that reached stability and group consensus at.	Primary: Majority said they would teach none of the big ideas at this education level.
			Secondary: Majority said "yes" for environmental factors of phosphorus, food systems, and phosphorus in agriculture.
			Undergraduate: Majority said yes for all four big ideas at this education level.

Table 2.4 (continued).

Survey Round	Number of Participants (n)	Task	Summary of Key Findings
			Graduate: Majority said yes for all four big ideas at this education level.

Table 2.5

List of Big Ideas Generated from Open-ended Responses

Definitional Big Ideas		Key Concept Big Ideas	
Circulating Phosphorus in a Closed Loop	Anthropogenic Impacts to Phosphorus Cycle	History of Phosphorus	Sources of Phosphorus
Conservation for the Future	Biological Properties of Phosphorus	Human Health Impacts	Sustainable Solutions
Decrease Dependency on Mined Phosphate	Chemical Properties and Structures of Phosphorus	Life Cycle Analysis	Systems Thinking
Environmental Pollution Mitigation	Economic Factors of Phosphorus	Mass Balances ("P Flow Diagram")	Regulations and Policies
Finite Resource	Environmental Factors of Phosphorus	Metrics, Units, and Data	Recovery and Recycling of Phosphorus
Healthy Ecosystems	Essential Element	Mining	Transdisciplinary Thinking
Phosphorus Sources	Finite Resource	Phosphorus Cycle	Waste Systems
Scales of Phosphorus	Fertilizers	Phosphorus in Agriculture	Wicked Problems
Sustaining and Improving Food Production	Food Systems	Physical Properties of Phosphorus	Utilization of Phosphorus in Plants
Three Pillars of Sustainability	Geological Properties of Phosphorus	Social Factors of Phosphorus	
	Geopolitics	Soil Sciences and Legacy Phosphorus	

Note. The definitional big ideas were generated from themes derived from responses to the first open-ended question from round 1.

The key concept big ideas were generated from themes derived from responses to the second open-ended question from round 2

Table 2.6

Round 2 Descriptive Statistics for Definitional Big Ideas

Big Idea	Mean	Std.
Environmental Pollution Mitigation	4.41	0.69
Circulating Phosphorus in a Closed Loop	4.24	0.95
Healthy Ecosystems	4.22	0.67
Sustaining and Improving Food Production	4.19	0.81
Scales of Phosphorus	4	0.88
Conservation for the Future	3.97	1.09
Phosphorus Sources	3.84	1.04
Decrease Dependency on Mined Phosphate	3.78	0.96
Three Pillars of Sustainability	3.75	1.00
Finite Resource [a]	3.59	1.28

Note. Definitional big ideas were derived from participant responses to the first open-ended question from round 1 (*In your own words, how should phosphorus sustainability be defined?)*.

[a] *Finite resource* was removed from the third-round survey to reduce the potential for survey fatigue and attrition among participants.

Table 2.7

Round 2 Descriptive Statistics for Key Concept Big Ideas

Big Idea	Mean	Std.
Environmental Factors of Phosphorus	4.41	0.69
Sustainable Solutions	4.22	0.85
Systems Thinking	4.22	0.87
Anthropogenic Impacts to Phosphorus Cycle	4.19	0.88
Food Systems	4.08	0.89
Recovery and Recycling of Phosphorus	4.05	1.00
Mass Balances (“P Flow Diagram”)	4.03	0.93
Phosphorus in Agriculture	4.03	0.99
Fertilizers	3.97	0.99
Geopolitics	3.97	0.93
Phosphorus Cycle	3.81	1.08
Economic Factors of Phosphorus	3.73	0.93
Essential Element	3.73	1.17
Sources of Phosphorus	3.73	0.96
Soil Sciences and Legacy Phosphorus	3.70	0.97
Transdisciplinary Thinking	3.59	1.36
Waste Systems	3.57	0.90
Wicked Problems	3.57	1.09
Social Factors of Phosphorus	3.54	1.04
Regulations and Policies [a]	3.49	1.02
Human Health Impacts [a]	3.43	1.09
Life Cycle Analysis [a]	3.41	0.98
Finite Resource [a]	3.32	1.11
Metrics, Units, and Data [a]	3.27	0.99
Utilization of Phosphorus in Plants [a]	3.19	1.02
Mining [a]	3.12	1.10
Chemical Properties and Structures of Phosphorus [a]	3.11	1.24
Physical Properties of Phosphorus [a]	3.05	1.03

Table 2.7 (continued).

Big Idea	Mean	Std.
Biological Properties of Phosphorus [a]	2.89	1.10
Geological Properties of Phosphorus [a]	2.86	0.95
History of Phosphorus [a]	2.84	1.17

Note. Key concept big ideas were derived from participant responses to the second open-ended question from round 1 (*What key concepts and skills should be taught in order to understand phosphorus sustainability?)*.

[a] These big ideas were removed from the third-round survey to reduce the potential for survey fatigue and attrition among participants.

Figure 2.3

Example of Edits Made to Big Idea Survey Items Between Rounds 2 and 3

Round 2 Original Version:

Big Idea: Decrease Dependency on Mined Phosphate
Summary
When defining phosphorus sustainability, it should mention reducing/decreasing the amount of mined phosphate humans extract from phosphate reserves to meet society's phosphorus needs.

Exemplary Supporting Statements
1) The reduction or elimination in mining of phosphate rock.
2) Have as little reliance on mined phosphorus as possible.
3) There is no (or very little) additional need for the mining of phosphorus for use in agricultural production.
4) Reduction of reliance of imported (mined) phosphorus).
5) Avoiding the use of newly mined products where possible.

Round 3 Emended Version:

Big Idea: Decrease Dependency on Mined Phosphate
Summary
When defining phosphorus sustainability, it should mention reducing the amount of mined phosphate that humans extract from phosphate reserves to meet society's phosphorus needs.

Exemplary Supporting Statements
1) Reduction of reliance on mined phosphate rock by recycling phosphorus already extracted from mines.
2) Have as little reliance on mined phosphate as possible in order to reduce monopolies, geopolitical insecurity, and world prices that make a reliance on imported mined phosphate a vulnerability for most regional/national food systems

Definitional Big Ideas

All ten *definitional* big ideas received a mean higher than 3.5, five of which were rated very important (≥ 4). Seven of these highly rated big ideas had a standard deviation <1, indicating a high consensus among the participants regarding the importance of including these big ideas when defining phosphorus sustainability. However, three of these highly rated big ideas did not have a high level of consensus ($\sigma \geq 1$) between the participants. Explanations or justifications for their high importance rating for these big ideas from participants included, "We are very behind technologically in the development of new materials for phosphorus capture, recovery, and reuse. I think this area needs significantly more emphasis" (Participant 9 in reference to *circulating phosphorus in a closed loop*) and "I think this is extremely important, but also redundant with the big ideas on *decrease dependency on mined phosphate* and *conservation for the future*. I personally prefer how this big idea is simple and to the point as compared to *decrease dependency on mined phosphate*" (Participant 8 in reference to *sustaining and improving food production*).

Even though the big idea of *finite resource* had an average rating of importance greater than 3.5, this item had the most variation among participants ($\sigma = 1.28$). Several participants expressed caution regarding including the concept of "finite" in a phosphorus sustainability definition. For example, Participant 5 wrote, "important, but the finite reserves arguments can detract from the real issues." Similarly, Participant 38's critiquing stated:

> Phosphorus isn't a finite resource. Some of the primary sources specific places are finite, like rock P from Morocco, but phosphorus is also an element that exists in all organic matter, as well as water and soils. I find it helpful to frame it as a demand, recovery, and

distribution problem based on sourcing choices, not a supply problem. I would be cautious about mentioning finitude in any definitions.

Due to the high level of variation and participant suggestions, *finite resource* was removed from the third round of the Delphi study to limit survey fatigue and participant attrition.

Key Concept Big Ideas

Nineteen of the *key concept* big ideas had an average rating of 3.5 or higher, with eight rated as very important (≥ 4). These nineteen key concepts were considered important to learn to understand phosphorus sustainability during the second round. As seen in Participant 12's statement about the big idea of the *environmental impacts of phosphorus*, "Most people have no clue about this, so it has to be a part of the conversation." Similarly, Participant 2 wrote, "If we want to get to a place where students understand the real barriers to any kind of sustainability, this is vital," in reference to *economic factors of phosphorus*. Thirteen of these big ideas that had an average rating of 3.5 or higher had high consensus ($\sigma < 1$) among the panel, while six did not ($\sigma \geq 1$).

The participants found twelve *key concept* big ideas unimportant ($\bar{x} < 3.5$). Reasons for low ratings for these big ideas provided by participants included "covered in other topics" (Participant 12 in reference to *healthy ecosystems*), "in my experience, this isn't a very effective or easily understandable tool" (Participant 23 regarding *life cycle analysis*), and "this feels too advanced for K-12 or the general public, but definitely appropriate for juniors and seniors in college and beyond," (Participant 2 in reference to *physical properties of phosphorus*). The three least important *key concepts* big ideas from the group were the *biological properties of phosphorus* ($\bar{x} = 2.89$), *geological properties of phosphorus* ($\bar{x} = 2.86$)*, and history of phosphorus* ($\bar{x} = 2.86$). Participant 8's explanation for not rating geological properties of

phosphorus as important was, “I think this is very important for someone to understand if they will be working on phosphorus sustainability, but I don’t think understanding the geological properties of phosphorus is important for understanding the concept of phosphorus sustainability.” Regarding the big idea *history of phosphorus*, four participants mentioned that while they find the concept interesting, they do not see it as essential for understanding phosphorus sustainability. The twelve big ideas with a panel rating of less than 3.5 were removed from the succeeding round to diminish survey fatigue and attrition.

Round 3

Thirty-four out of thirty-seven participants completed the third round of the Delphi study, and the attrition rate between the second and third rounds was 8.11%. Participants’ round 2 responses reduced the round 3 survey from 41 to 28 big ideas. Table 2.8 (*definitional* big ideas) and Table 2.9 (*key concept* big ideas) report the means and standard deviations for participants' importance ratings for each of the 28 big ideas included in the third round. Six *definitional* big ideas and sixteen *key concept* big ideas reached stability within the group after the third round (see Tables 7 and 8). After the third round, five *definitional* big ideas and six *key concept* big ideas achieved group consensus (see Tables 2.8 and 2.9). The total number of big ideas between the *definitional* (n=4) and *key concepts* (n=4) that achieved both group stability and consensus was eight. The following subsections describe the details regarding these eight agreed-upon big ideas and address the study’s first three research questions.

Twenty big ideas did not attain stability and/or group consensus, excluding them from the list of concepts for understanding phosphorus sustainability or from being included in the definition of phosphorus sustainability. Participants provided a variety of reasons why they rated these big ideas as unimportant. In reference to the big idea of *three pillars of sustainability*,

Participant 19 wrote, “To me, the idea of pillars for sustainability is very outdated.” Other participants felt that this big idea (*three pillars of sustainability)* was too broad and required actions that could be unclear or hard to explain. For example, Participant 23’s explanation stated, “*Three pillars of sustainability* is probably the hardest to quantify and explain to a diverse group of stakeholders.

Two frequently occurring explanations given by participants for various big ideas being ranked unimportant were because they felt the concept should be covered in the discussion of other big ideas or the big idea was too complex or not essential for the average learner to know. Participant 44 mentioned, “I feel like this idea [*mass balances*] is too technically in-depth for many students. Many of these concepts are or could be incorporated into the big idea of the *phosphorus cycle*.” Participant 14 stated, “*Systems thinking* is critically important, but the wording and rationale here is very similar to *wicked problems* and *transdisciplinary thinking*. There may be an opportunity to combine these three ideas into just two.” When discussing the big idea of *economic factors of phosphorus*, Participant 8 noted, “I think this concept is important to understand if educating an audience that will try to develop solutions to phosphorus sustainability challenges, but I don’t think this topic needs to be understood in order to grasp the concept of phosphorus sustainability.” Another common reason was that participants sometimes felt the big idea was not uniquely specific to phosphorus sustainability. For example, “While it is true that P is an essential element, it is not the only one. H, C, N, O, Mg, S, Ca, Cu, Zn, and Mo, are all equally as essential to life” (Participant 37 in reference to *essential element*).

Phosphorus Sustainability Definition

The expert panel identified four big ideas that should be incorporated into the definition of phosphorus sustainability. These big ideas were *circulating phosphorus*, *environmental*

Table 2.8

Round 3 Descriptive Statistics, Stability, and Group Consensus Achievement for Definitional Big Ideas

Big Idea	Mean	Std.	Spearman's rho (ρ)	Stability (Y/N)	% of participants rating >4 (%)	Group Consensus (Y/N)
Environmental Pollution Mitigation	4.29	.719	**.621****	Y	**91.12%**	Y
Circulating Phosphorus	4.26	.666	**.417***	Y	**88.24%**	Y
Healthy Ecosystems	4.24	.819	**.420***	Y	**82.35%**	Y
Sustaining and Improving Food Production	4.09	.866	**.613****	Y	**73.53%**	Y
Conservation for the Future	3.85	.958	.574**	Y	58.82%	N
Decrease Dependency on Mined Phosphate	3.85	1.105	.195	N	67.65%	Y
Three Pillars of Sustainability	3.68	1.007	.205	N	58.82%	N
Phosphorus Sources	3.65	.917	.289	N	61.76%	N
Scales of Phosphorus	3.65	1.152	.515**	Y	55.88%	N

Note. Stability is achieved when Spearman's correlation coefficient is statistically significant ($p<.05$). Group consensus is achieved when two-thirds (66%) or more participants rated the big idea as very important or extremely important. Big ideas achieving both stability and group consensus have their Spearman's value and percentage of participants rating >4% in bold.

*Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).

Table 2.9

Round 3 Descriptive Statistics, Stability, and Group Consensus Achievement for Key Concept Big Ideas

Big Idea	Mean	Std.	Spearman's rho (ρ)	Stability (Y/N)	% of participants rating >4 (%)	Group Consensus (Y/N)
Phosphorus in Agriculture	4.35	.734	**.606****	Y	**85.29%**	Y
Recovery and Recycling of Phosphorus	4.06	.694	**.600****	Y	**79.41%**	Y
Anthropogenic Impacts to Phosphorus Cycle	4.03	.969	.077	N	82.35%	Y
Environmental Factors of Phosphorus	4.03	.758	**.552****	Y	**79.41%**	Y
Food Systems	4.00	.921	**.531****	Y	**70.59%**	Y
Systems Thinking	3.97	.797	.318	N	73.53%	Y
Phosphorus Cycle	3.79	1.028	.547**	Y	64.71%	N
Essential Element	3.76	1.156	.721**	Y	64.71%	N
Sustainable Solutions	3.76	1.046	.413*	Y	64.71%	N
Soil Sciences	3.74	.864	.541**	Y	61.76%	N
Mass Balances ("P Flow Diagram")	3.65	1.203	.400*	Y	52.94%	N
Sources of Phosphorus	3.65	.981	.535**	Y	52.94%	N
Economic Factors of Phosphorus	3.59	.925	.372*	Y	47.06%	N
Transdisciplinary Thinking	3.59	1.184	.442**	Y	52.94%	N
Waste Systems	3.56	.860	.480**	Y	55.89%	N
Social Factors of Phosphorus	3.56	1.186	.551**	Y	58.82%	N
Fertilizers	3.53	.896	.567**	Y	44.12%	N

Table 2.9 (continued).

Big Idea	Mean	Std.	Spearman's rho (ρ)	Stability (Y/N)	% of participants rating >4 (%)	Group Consensus (Y/N)
Wicked Problems	3.53	1.080	.661**	Y	52.94%	N
Geopolitics	3.35	.849	.338	N	47.06%	N

Note. Stability is achieved when Spearman's correlation coefficient is statistically significant ($p<.05$). Group consensus is achieved when two-thirds (66%) or more participants rated the big idea as very important or extremely important. Big ideas achieving both stability and group consensus have their Spearman's value and percentage of participants rating >4% in bold.

*Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).

pollution mitigation, *healthy ecosystems*, and *sustaining and improving food production*. Participants rated these four big ideas highly because they felt they were specific concepts for phosphorus sustainability. As seen in Participant 2's justification for rating *circulating phosphorus* as "very important," "It's more specific to phosphorus. There are plenty of resources that are much harder to recover and reuse." Participants' feedback for sustaining and improving food production included comments such as, "This [sustaining and improving food production] will become THE most important over time" (Participant 23) and "Any changes in activities that impact the P-flow diagram could be very important in achieving sustainability" (Participant 9). Several participants stated they found *environmental pollution mitigation* and *healthy ecosystems* important to include when defining phosphorus sustainability because they are interconnected. For example, "This [*environmental pollution mitigation*] feels like the flip side of the coin for healthy ecosystems" (Participant 9).

The following definition of phosphorus sustainability (Figure 2.4) was generated utilizing the four big ideas the panel agreed upon for being important to include.

Figure 2.4

Definition of Phosphorus Sustainability

Phosphorus sustainability is the utilization of phosphorus to meet societal needs for agricultural food production while maintaining the soil health and water quality of the environment by mitigating the amount of phosphorus pollution entering the environment from human activities through improved management practices and policies that include, but not limited to, the recapturing and recycling of phosphorus from waterways, soil, manure, food waste, and human sewage.

Critical Concepts for Understanding Phosphorus Sustainability

The expert panel identified four concepts as essential for learners to gain knowledge of phosphorus sustainability. These key concepts were e*nvironmental factors of phosphorus*, *food systems*, *phosphorus in agriculture*, and *recovery and recycling of phosphorus*. One explanation for addressing *phosphorus in agriculture* as a key concept for understanding phosphorus sustainability was, "as a main user of phosphorus and source of pollution, this point is key" (Participant 38). Similarly, the big idea of *recovery and recycling of phosphorus* was also considered a fundamental component that people should understand, "again, this is important for people to understand solutions or solution pathways for phosphorus issues" (Participant 38). In reference to *food systems*, participants' explanations included "I prefer this topic to the one on fertilizers" (Participant 38) and "The main phosphorus problem comes from the need for it in food production" (Participant 38).

Agreement Rating Differences Based On Disciplinary Background

A one-way Analysis of Variance (ANOVA) was used to determine if there was a significant difference in the average importance rating between experts with science, engineering, social science/policy, or interdisciplinary backgrounds. Participants with professional experience in two or more fields derived from different disciplinary areas (e.g., disciplinary experience in engineering and social science) were placed in the interdisciplinary group. ANOVAs were conducted for the survey results for the second and third rounds. There were no significant differences ($p \leq .05$) in mean ratings between the four disciplinary background groups for any of the big ideas.

In round 3, there was a statistically significant mean difference ($p \leq .05$) between the four disciplinary groups for four of the big ideas (*circulating phosphorus* $F[3, 30] = 4.261$, $p = .013$,

n^2 = .299, *geopolitics* F[3, 30] = 4.508, p = 0.01, n^2= .311, *mass balances* F[3, 30] = 5.864, p = .003, n^2= .370, and *systems thinking* F[3, 30] = 3.019, p = .045, n^2= .232). A post-hoc Tukey's test (see Table 2.10) showed that the interdisciplinary group rated *circulating phosphorus* more important than the science group. Post-hoc Tukey's test results for *geopolitics* showed the social science/policy group rated the big idea as more important than the engineering and the interdisciplinary groups. The interdisciplinary group rated the big idea of mass balances as less important than both the engineering and social science groups. For systems thinking, the engineering group rated the big idea higher than the science group.

Round 4

The final round of this study asked participants to indicate education levels (primary, secondary, undergraduate, and graduate) for the key concepts (*environmental factors of phosphorus, food systems, phosphorus in agriculture, and recovery and recycling of phosphorus*). Thirty-two out of thirty-four participants completed the survey. Table 2.11 shows the educational selections noted by the participants.

Most of the experts agreed that the concept of *environmental factors of phosphorus* should be taught at the secondary (n=30, 93.34%), undergraduate (n=26, 81.25%), and graduate (n=17, 53.13%) education levels. Only seven (21.88%) participants thought primary students should receive education on this concept. The expert panel noted that students at the secondary (n=24, 75.00%), undergraduate (n=27, 84.38%), and graduate (n=17, 53.13%) level should be educated on the concept of *food systems*. The panel's ratings were similar for the concept of *phosphorus in agriculture,* with a majority of the panel stating this concept should be taught at the secondary (n=24, 75.00%), undergraduate (n=28, 87.50%), and graduate (n=19, 59.37%)

Table 2.10

Round 3 Post-hoc Tukey's Test Results

Big Idea	Disciplinary Group (I)	Disciplinary Group (J)	Mean Diff. (I-J)	Std. Error	p-value
Circulating Phosphorus	Science	Engineering	.000	.283	1.000
		Social Science/Policy	.000	.341	1.000
		Interdisciplinary	-.750*	.244	.022
	Engineering	Social Science/Policy	0.000	.366	1.000
		Interdisciplinary	-.750	.278	.052
	Social Science/Policy	Interdisciplinary	-.750	.337	.140
Geopolitics	Science	Engineering	-.571	.357	.394
		Social Science/Policy	-1.500*	.431	.008
		Interdisciplinary	-.167	.308	.948
	Engineering	Social Science/Policy	-.929	.463	.209
		Interdisciplinary	.405	.351	.661
	Social Science/Policy	Interdisciplinary	1.333*	.427	.019
Mass Balances	Science	Engineering	-1.117	.484	.119
		Social Science/Policy	-1.295	.585	.142

Table 2.10 (continued).

Big Idea	Disciplinary Group (I)	Disciplinary Group (J)	Mean Diff. (I-J)	Std. Error	p-value
		Interdisciplinary	.538	.418	.579
	Engineering	Social Science/Policy	-.179	.628	.992
		Interdisciplinary	1.655*	.476	.008
	Social Science/Policy	Interdisciplinary	1.833*	.578	.017
Systems Thinking	Science	Engineering	-1.026*	.354	.033
		Social Science/Policy	-.705	.428	.369
		Interdisciplinary	-.371	.306	.623
	Engineering	Social Science/Policy	.321	.459	.896
		Interdisciplinary	.655	.348	.258
	Social Science/Policy	Interdisciplinary	.333	.423	.859

*The mean difference is significant at the .05 level

Table 2.11

Participants Opinions on Which Education Levels Key Concepts Should be Taught in (n=32)

Key Concept	Primary				Secondary				Undergraduate				Graduate			
	Yes		No		Yes		No		Yes		No		Yes		No	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Environmental Factors of Phosphorus	7	21.88	25	78.12	30	93.34	2	6.66	26	81.25	6	18.75	17	53.13	15	46.88
Food Systems	13	40.63	19	59.37	24	75.00	8	25.00	27	84.38	5	15.63	17	53.13	15	46.88
Phosphorus in Agriculture	9	28.13	23	71.87	24	75.00	8	25.00	28	87.50	4	12.50	19	59.37	13	40.63
Recovery & Recycling of Phosphorus	3	9.38	29	90.62	10	31.25	22	68.75	29	90.62	3	9.38	25	78.12	7	21.88

education levels. Most participants felt that *food systems* (n=19, 59.37%) and *phosphorus in agriculture* (n=23, 71.87%) should not be introduced to primary students. Most of the participants viewed the concept of *recovery and recycling of phosphorus* as big ideas to be taught to higher education students. Twenty-nine (90.62%) participants agreed that the concept should be taught to undergraduate students, and 25 (78.12%) participants thought this concept should be taught to graduate students. Most participants agreed that secondary students (n=10, 31.25%) and primary students (n=29, 90.62%) should not be taught this concept

Discussion

The phosphorus sustainability researchers' perspectives provided a definition and set of key concepts on phosphorus sustainability that can be used as a framework for new educational resources and curricula.

Defining Phosphorus Sustainability

Educational communities can guide phosphorus sustainability education with the comprehensive definition generated by this Delphi study. Sustainability is a buzzword that is used frequently in media, academic disciplines, and by numerous stakeholders (Fischler, 2014; Little, 2014; Palmer et al., 1998); however, this poorly defined term has led to poor communication, misunderstandings, and limits meaningful collaboration (Palmer et al., 1998). These challenges have also spread to learning environments where elusive definitions of sustainability have created challenges with sustainability instruction, lesson design, and student learning (Urdan & Luoma, 2020). The comprehensive definition developed by the experts in this study can assist educators in avoiding negative impacts and barriers.

The participants in this study defined phosphorus sustainability as the utilization of phosphorus to meet societal needs for agricultural food production while maintaining the soil

health and water quality of the environment by mitigating the amount of phosphorus pollution entering the environment from human activities through improved management practices and policies that include, but not limited to, the recapturing and recycling of phosphorus from waterways, soil, manure, food waste, and human sewage. This definition includes four big ideas (*circulating phosphorus*, *environmental pollution mitigation*, *healthy ecosystems*, and *sustaining and improving food production*) agreed upon through group stability and consensus by the Delphi participants. While there were initially ten potential big ideas that could have been chosen to be included in the definition, these four were found to be the most important by the participants. These four big ideas are consistent with themes commonly promoted across phosphorus sustainability literature. Researchers have emphasized the importance of phosphorus recycling and recovery from the environment and waste (Barquet et al., 2020; Chowdhury et al., 2017; Jacobs et al., 2017), food production and mining impacts on phosphorus runoff and water quality issues (Chowdhury et al., 2017; Scherer & Pfister, 2016; Zhang et al., 2022), and the critical role phosphorus plays in feeding the global population (Helin & Weikard, 2019).

This Delphi study concluded with three definitional big ideas (*decrease dependency on mined phosphate rock*, *phosphorus sources*, and *three pillars of sustainability*) not reaching group stability, meaning there was a large shift in the distribution of responses between the second and third rounds. Additional rounds of editing and Likert ratings with the expert panel might have allowed stability to occur, resulting in a consensus on these ideas; however, financial costs, time, and increased risks of participant attrition associated with further rounds prevented this from occurring.

Recommendations for Defining Phosphorus Sustainability

It is important that definitions of phosphorus sustainability highlight the role food production plays in the system because, as stated by one of the participants, sustaining and improving food production "will become THE most important over time." The agriculture industry, which is responsible for feeding the world, is the primary consumer of both mined and recycled phosphorus, and it is estimated that global phosphorus demand will double by the end of the century (Helin & Weikard, 2019). Instead of highlighting sustaining access to phosphorus solely for food production, other definitions of phosphorus sustainability could be broader and state "to meet societal needs for phosphorus" or specifically list other industries (e.g., detergents, electric cars); however, these other commercial usages of phosphorus only account for 10 to 20% of the worldwide demand for phosphate rock (Childers et al., 2011). Due to the more prominent role and impact food production plays in phosphorus sustainability, it is recommended that educators, like the experts in this study, focus on food production rather than all commercial industries that utilize phosphorus.

Approximately 80% of mined phosphate is lost to the environment (Childers et al., 2011), which could explain why the three highest-rated definitional big ideas by participants in this study were *circulating phosphorus*, *environmental pollution mitigation*, and *healthy ecosystems*. Eutrophication in surface waters due to phosphorus pollution creates water quality, biodiversity loss, human health, and economic challenges (Jacobs et al., 2017; Stamm et al., 2022). Preventing and recovering phosphate from the environment will assist in creating a more sustainable phosphorus system (Brownlie et al., 2022; Yuan et al., 2018); therefore, it is important that educators address these environmental factors and solutions when defining phosphorus sustainability for students.

In 2009, it was estimated that current global reserves of phosphate rock would be depleted in the next 50 to 100 years (Cordell et al., 2009); however, revisions of phosphate reserves and resources estimates (Edixhoven et al., 2014; Scholz & Wellmer, 2016), the potential discovery of new sources of phosphate (Ibrahim et al., 2016), and technological advances (e.g., economic underground mining) have pushed the timeline for depletion back hundreds of years (Heckenmüller et al., 2014). These new estimates have shifted the emphasis surrounding phosphorus from resource scarcity to the environmental pollution impacts of phosphorus usage (Edixhoven et al., 2014), which could explain why the participants found the big idea of *conservation for the future* less of a priority to include when defining phosphorus sustainability. Some of the experts in this Delphi study expressed similar shifts in emphasis by agreeing that the big ideas of *environmental pollution mitigation* and *healthy ecosystems* are more important to include when defining phosphorus sustainability than *conservation for the future.* Several participants in this study described how *conservation for the future* is currently not as important to them as other concepts when defining phosphorus sustainability as a result of developing technology that will improve humanity's ability to recover phosphorus. The results from this Delphi study suggest emphasizing the more immediate risks that will impact students, such as environmental risk, over future risks when defining phosphorus sustainability.

The Key Concepts of Phosphorus Sustainability

Until now, educators have not had access to guidance about key concepts that are necessary for students to learn to understand phosphorus sustainability. While educators have access to lists of essential concepts for sustainability literacy (e.g., El Ansari & Stibbe, 2009), these concepts were not explicitly developed for phosphorus sustainability. Delphi participants agreed that the big ideas of e*nvironmental factors of phosphorus*, *food systems*, *phosphorus in*

agriculture, and *recovery and recycling of phosphorus* were key concepts one would need to understand phosphorus sustainability. Using the recommendations provided by the experts in this study, the educational community can begin developing curricular coherence around these four concepts. There are several documented barriers to learning about sustainability, including a lack of effective curricular materials, a focus on high-stakes assessments, a focus on cognitive dimensions of learning, a lack of effective curricular materials, and little time for collaborative curriculum development (Parry & Metzger, 2023). Developing curricular coherence for phosphorus sustainability can assist teachers in overcoming these barriers because curricular coherence assists with developing effective learning environments that align content and the sequencing of teaching topics to students (Fortus et al., 2015).

Table 2.11 suggests teaching phosphorus sustainability concepts across several different education levels (secondary education through graduate education); however, participants were less likely to suggest teaching any of the concepts at the primary level. One potential reason could be that participants are more familiar with students' cognitive abilities or curricula topics for secondary and higher education students than primary students. Future research should involve experts in primary education to help discover possible phosphorus sustainability concepts that could be included in primary curricula. While participants recommended teaching all four concepts to undergraduate and graduate students, the undergraduate level received more yeses than the graduate level. A possible explanation for this could be that participants have different views of the goals behind undergraduate and graduate education. Undergraduate degrees aim to provide students with a broad knowledge base, while graduate degrees provide specialized knowledge for a specific career. The participants in this study might have felt that

only graduate students pursuing a career in phosphorus sustainability would need these four concepts included in their studies.

One of the challenges observed in this study was the overlapping of themes across the big ideas. Several participants reported it was hard to rate the level of importance because they felt some of the big ideas were too similar or shared similar supporting statements. The participant's desire to have distinct, non-overlapping concepts could have influenced their importance rating for these fifteen big ideas. Prior studies exploring sustainability literacy concepts have reported that it is challenging to classify each concept into discipline-based education because several of the concepts overlap with each other; however, these studies argue that classifying these concepts into strict disciplines is undesirable, unlike the participants in this study (El Ansari & Stibbe, 2009).

The big ideas of *anthropogenic impacts to the phosphorus cycle* and *systems thinking* received more than two-thirds of the panels rating the big ideas as very or extremely important; however, neither reached group stability. As stated for the three definitional big ideas that did not achieve group stability, group stability might have occurred with additional rounds of editing; however, financial costs, time, and increased risks of participant attrition associated with further rounds prevented this from occurring.

Future research will need to be conducted to discover additional phosphorus sustainability concepts to include in curricula. While the Delphi method was used for this study, researchers can utilize other research techniques (e.g., literature reviews) to discover additional key concepts. In the meantime, the four concepts outlined by the participants in this study can serve as the foundational steppingstones for the education community to begin incorporating phosphorus sustainability into education learning environments.

Recommendations for Educators When Teaching Key Concepts

The key concept of *environmental factors of phosphorus* was summarized by participants as understanding the role of phosphorus in the environment, including the impacts of having too much or too little. It is important that when educators are teaching about phosphorus' role and impact on the environment, educators acknowledge that while having too much phosphorus can cause a ripple of negative consequences, having too little phosphorus in the environment can also trigger negative impacts. This dichotomous concept is known as the phosphorus paradox (Lougheed, 2011). The results of this study suggest that students need to understand that the presence of phosphorus in the environment is natural and necessary; without phosphorus, all living things would not be able to survive (Elser, 2012). For many parts of the developing world, especially in tropical places, soil quality is poor, containing low levels of phosphorus, and there are limited financial resources to supplement the soil with phosphorus-rich fertilizers (Shepherd et al., 2016). When plants are deficient in phosphorus due to the lack of availability in their environment, the photosynthetic capacity of plants is diminished, and the growth rate is reduced (Plénet et al., 2000). Educators should be careful when framing their education messages to avoid developing misconceptions among students that the presence of phosphorus in the environment is bad.

According to the experts in this study, instruction should emphasize the nutrient limitations of aquatic environments and the consequences of nutrient imbalances, such as eutrophication, due to excess phosphate loading. When teaching eutrophication, emphasizing the personal impacts of recreational activities, drinking water treatment, and ecosystem diversity can engage students with the topic (Penn & Bowen, 2018). For example, the relevancy to humans and pets can be shown by highlighting the impact of algae that are produced during

eutrophication, releasing toxins into the water that can cause illness or death in pets or humans that ingest the toxins (Penn & Bowen, 2018).

Participants in the study conceptualized the key concept of *food systems* as understanding the role phosphorus plays in food production. For *phosphorus in agriculture*, participants described the concept as knowledge of phosphorus's roles in agriculture systems (e.g., meeting the nutritional needs of livestock and crops) and the impacts agriculture has on the phosphorus cycle. Participants in the study stressed the importance of understanding phosphorus's role in food and agriculture and the challenges of phosphorus (e.g., excess phosphorus runoff) that are driven by the need for phosphorus in food production. These phosphorus researchers suggest that educators address the role diet choices and food waste play in phosphorus sustainability instruction.

Many of the challenges associated with phosphorus sustainability are systemic problems that the average person has little control and action over; however, one area where students can make an impact is diet choices and food waste. Since 1970, the average human dietary phosphorus footprint has increased globally by 38% due to the increasing consumption of animal products over plant-based products in human diets (Metson et al., 2012). Livestock feed is one of the key factors driving global phosphorus demand (Helin & Weikard, 2019), so reducing the demand for meat through diet changes will decrease the global need for phosphorus. Additionally, one-third of the food produced globally is wasted (Sharma et al., 2020). Researchers found that 424,400 tons of phosphorus is lost in China annually due to food waste (Li et al., 2020). Educating students about the positive impacts of diet choices and decreasing food waste has the potential to develop pro-environmental behaviors in students. Research has shown that students' knowledge of human-environment relationships and knowledge of

behavioral choices and environmental actions that can reduce environmental problems can promote pro-environmental behaviors (Janmaimool & Khajohnmanee, 2019).

The participants summarized the *recovery and recycling of phosphorus* as understanding the role that these activities will have in the sustainable use of phosphorus. Based on participants' responses in this study, it is recommended that educators emphasize that recovery and recycling are already strategies that are being implemented when teaching this concept. If this is not explicitly acknowledged, students might develop misconceptions that recycling and recovering phosphorus technologies do not exist despite the availability of hundreds of technologies and strategies (Scholz & Hirth, 2015). Instead of emphasizing the need to develop new technologies, the experts in this study recommend that educators highlight the importance of implementing currently available technologies. Additionally, it is recommended that educators acknowledge that no system can be 100% recoverable and that some loss will always occur. Researchers have shown that people can develop misconceptions about the realistic expectations and efficiencies of recycling and recovering resources, which can mislead decisions made by policymakers or the public (Giampietro & Funtowicz, 2020; Scholz & Hirth, 2015).

Limitations

As previously mentioned, time, costs, and the size of the participant pool were limitations for this study. This Delphi study was time and energy-intensive for both the researchers conducting it and the participants, thus preventing the inclusion of more survey rounds, which could have revealed additional key concepts. Despite the best efforts to make the expert panel as diverse as possible, including more experts from disciplines that were either not represented or underrepresented could contribute to different perspectives and broaden the list of key concepts or expand the definition of phosphorus sustainability. For example, due to the low frequency of

participants with social science and participants with policy backgrounds, these disciplinary fields had to be combined into one professional group. Social science and policy researchers may have different perspectives from each other; however, being included in a group together, it was not feasible to observe these potential differences.

Conclusion

There is a need to develop and implement phosphorus sustainability education. Educators can use the definition in this study to provide their students with a clear and concise description of phosphorus sustainability. The findings discovered in this study can guide the development of curricular coherence that appropriately align phosphorus sustainability concepts with curricula, lessons, and assessments. As this study has highlighted, phosphorus sustainability is important to food production and a healthy environment. Continuing to invest in the development of phosphorus sustainability education can ensure a healthier and prosperous future for ourselves and the planet.

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CHAPTER 3: Leveraging the expertise of scholars to address the silent crisis of phosphorus through education

Abstract

There is a growing phosphorus sustainability crisis that is relatively unknown to most of the world. Many of Earth's surface waters face the threat of eutrophication due to excess phosphorus runoff from non-point sources (e.g., agriculture fields and livestock waste), threatening the health of humans and aquatic ecosystems. While other sustainable challenges have received attention from the educational community, there is a dearth of educational research on this topic. Twenty researchers with experience and expertise in phosphorus sustainability (science, engineering, social science, and policy fields) were interviewed to document their knowledge and perceptions about teaching and learning about phosphorus sustainability. Analyses revealed a variety of perspectives and a consensus of recommendations for teaching and learning phosphorus sustainability. Major themes included integrating systems thinking and interdisciplinary learning into lessons and empowering learners to partake in pro-environmental behavior. Potential challenges for educators raised by participants included a lack of empathy from learners due to the overload of environmental issues they face, the complexity embedded in phosphorus sustainability, finding time and space to incorporate lessons into the current curriculum, and forced censorship from authorities (e.g., administrators, school boards, politicians). Recommendations for future research and implications are discussed.

Introduction

Human population growth and technological advances have led today's society to face a multitude of sustainability challenges (e.g., climate change, deforestation, biodiversity loss). These sustainability challenges threaten the health and safety of both the human population and the environment. Prior to the Industrial Revolution, Earth's environment had remained stable for 10,000 years, allowing the rise of a thriving human civilization (Rockström et al., 2009; Steffen et al., 2007). The onset of the Industrial Revolution and, subsequently, the exponential growth of the human population created unprecedented human-generated environmental issues.

The biogeochemical cycling of phosphorus has been classified by researchers as an important component in regulating the stability of Earth's ability to support human life (Rockström et al., 2009). Human activities (e.g., phosphate mining) have interfered with the biogeochemical flow of phosphorus in nature (Rokstrom et al., 2009). Anthropogenic impacts on the phosphorus cycle threaten the homeostasis of Earth's environmental systems and increase the risk of wide-scale and potentially irreparable environmental harm, impacting Earth's ability to support the human population (Rockström et al., 2023). Humanity's unsustainable impacts on the biogeochemical cycling of phosphorus are causing environmental harm and threatening human life, making the sustainable management of phosphorus a growing area of interest for science education.

There is a growing urgency to provide phosphorus sustainability education worldwide. The *Our Phosphorus Future* report, developed by over 50 researchers, stresses an urgent need for phosphorus sustainability education in order to increase phosphorus sustainability initiatives and infrastructure (e.g., recycling phosphorus; Brownlie et al., 2022). The present study takes a first step in addressing this need by examining the knowledge and perspectives of phosphorus

sustainability experts to create an educational framework that can guide the development and implementation of phosphorus sustainability literacy curricula and lessons.

The Phosphorus Sustainability Problem

Phosphorus, an essential nutrient for all life, plays a critical role in food production. Most of the world's food is grown using chemical fertilizers containing phosphate, a natural source of phosphorus found in nature that is mined from either sedimentary or igneous rocks (Fayiga & Nwoke, 2016). Before the widespread use of chemical fertilizers, agriculture relied on organic fertilizers (e.g., manure, compost, bone meal) to provide phosphate to their crops (Russel & Williams, 1977). Mining phosphate rock for commercialized fertilizers has shifted the phosphorus cycle, allowing large amounts of phosphorus to be shipped worldwide. Even though phosphorus is an important nutrient for all ecosystems, anthropogenic impacts on the phosphorus cycle via mining, agriculture practices, and waste systems have led to an overabundance of this nutrient in many soils and aquatic environments (Yuan et al., 2018). The pollution of surface waters (freshwater or saltwater) from phosphorus runoff leads to costly eutrophication events (Jacobs et al., 2017). During these eutrophication events, excessive algae growth occurs, depleting water oxygen levels. Decreased oxygen levels and toxic compounds released from the excess algae kill the surrounding aquatic organisms, leading to a significant loss of biodiversity (Scherer & Pfister, 2016), disruption to food webs (Wang et al., 2023), and impacts on the health of humans (Liu & Klaiber, 2023).

In addition to the water quality problems caused by phosphorus runoff, there is a growing concern over equitable access to phosphate for food production due to diminishing phosphate reserves (Filippelli, 2018). These unsustainable issues with phosphorus were created due to human behavior and actions and will require changes to become more sustainable. Education can

play a critical role in fostering this change. Sustainability education allows individuals to develop knowledge, skills, and an understanding of values and solutions to create a more sustainable system (Nevin, 2008).

Literature Review

Sustainability is a paradigm for thinking about the future where environmental, societal, and economic considerations are equitably and justly balanced for the betterment and preservation of society. Sustainability is often discussed within the context of sustainable development. While the two terms are often used interchangeably, sustainability is viewed as a long-term goal, and sustainable development is the process and pathway to achieve it (Jeronen, 2013). The World Commission on Environment and Development defines sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (Thomsen, 2013, p.2358).

Sustainability Education Initiatives

Recognizing the critical role education plays in increasing sustainable development, in 2002, the United Nations kick-started a global movement for sustainability across all education levels through their Decade of Education for Sustainable Development initiative (Žalėnienė & Pereira, 2021). This decade took place from 2005 to 2014 and focused on integrating sustainable development principles, values, and practices across all aspects of education and learning (Brunold, 2006). When that decade ended, the United Nations launched a new initiative for the international community to work towards from 2015 to 2030 called the Sustainable Development Goals (SDGs). This initiative consists of 17 interconnected goals designed to be universally applicable to developed and developing countries (Vladimirova & Le Blanc, 2016). These 17

goals offer practical and effective actions to address causes of violent conflict, human rights abuses, climate change, and environmental degradation through economic growth, social well-being, and environmental protection (United Nations, 2018). The fourth SDG is Quality Education. The UN has outlined ten targets related to the goal of Quality Education. One of these targets addresses that by 2030, all learners will have the knowledge and skills needed to promote sustainable development by receiving education on sustainable development and sustainable lifestyles, human rights, global citizenship, and appreciation of cultural diversity (Giangrande et al., 2019; UNESCO, 2020).

Sustainability Education

Educators play an important role in helping learners understand the complexities of sustainability and facilitate and motivate learners to transform their and society's ways of life (UNESCO, 2020). After the launch of Education for Sustainable Development (ESD), studies have shown that ESD positively impacts students' sustainability literacy (Benavot, 2014; Pauw et al., 2015).

Research suggests that effective ESD should integrate sustainability across all subject areas and provide professional development opportunities for teachers to assist with implementing ESD learning into the curriculum (Laurie et al., 2016). Recommended pedagogical strategies for sustainability education include project/problem-based learning, integrative learning (inter- and transdisciplinary), active learning, collaborative learning, and experiential learning (Evans, 2019). Educational challenges associated with teaching sustainability include institutional constraints due to political influences, lack of familiarity with appropriate and effective pedagogical teaching strategies (e.g., constructivist inquiry-based learning), and a lack of knowledge and experiences with sustainability education (Evans, 2019).

Phosphorus Sustainability Education

While education for sustainable development has grown in prominence (Agbedahin, 2019), phosphorus sustainability has not been frequently addressed. For example, the *Next Generation Science Standards*, science content standards for K-12 education used throughout the United States, never specifically addresses phosphorus (National Research Council, 2013). However, the *Next Generation Science Standards* repeatedly mention other sustainable challenges (e.g., Climate Change) and essential elements (e.g., carbon, oxygen, hydrogen, and nitrogen). Phosphorus sustainability education has limited representation in education settings and literature. One study with undergraduate chemistry students described the learning impacts of a curriculum innovation project focused on phosphate recovery (Zowada et al., 2020). Despite these few select articles (Oerther et al., 2006; Seibert et al., 2020; Zowada et al., 2020), literature searches in Google Scholar, ERIC, and Web of Science have revealed a dearth of additional articles related to phosphorus sustainability education.

Investments in sustainability education in other areas have resulted in positive outcomes. For example, climate change education has led individuals to reduce their carbon footprints (Cordero et al., 2020), meat consumption (Jalil et al., 2023), and increase the number of people who view climate change as a major threat (Pew Research Center, 2019). Education can potentially result in similar increases in pro-environmental behaviors among society for phosphorus sustainability. Therefore, equipping educators with the knowledge and skills required for quality phosphorus sustainability education is critical.

Utilizing Expert Knowledge for Phosphorus Sustainability Education

Developing phosphorus sustainability education materials will require domain knowledge as well as an understanding of conceptual progressions. Domain knowledge encompasses an

individual's declarative, procedural, and metacognitive knowledge of a particular field (Bruning et al., 2011). Developing domain knowledge takes time, and studies have shown that developing expertise in a specific domain can take up to 10,000 hours or more (Bruning et al., 2011; Glaser, 1985). Experts' domain knowledge has been used previously to guide areas such as nanoscience education (Sakhnini & Blonder, 2015), environmental education (Clark et al., 2020), and sustainability education (Wright & Defields, 2012). Sustainability can be an ambiguous field (Salas-Zapata & Ortiz-Muñoz, 2019; Urdan & Luoma, 2020), and expert knowledge could guide the development of educational content (e.g., curricula, lessons, professional development). Having an expert framework for phosphorus sustainability can assist educators in interpreting complex information and avoiding misleading information.

Research Questions

To address the need for phosphorus sustainability education, this study examined the knowledge and perspectives of researchers who study phosphorus sustainability. This information can form the preliminary foundation educators need to implement phosphorus sustainability into their teaching and to develop educational content. The following research questions were examined:

RQ1. How do researchers who study phosphorus conceptualize phosphorus sustainability?

RQ2. What are the perspectives of researchers who study phosphorus regarding the skills and knowledge that are important for understanding phosphorus sustainability?

RQ3. How do researchers who study phosphorus think phosphorus sustainability education should be structured?

RQ4. What are the perspectives of researchers who study phosphorus regarding the challenges of phosphorus sustainability education?

Theoretical Framework: Communities of Practice

This study is informed and guided by the social theory of learning: Communities of Practice (CoP). CoP is built on the premise that learning is a social process where people who share a concern, set of problems, or passion for something they do come together as a group to learn how to do it better (Lave & Wenger, 1991). Lave and Wenger (1991) outlined three components a group of individuals needs to be classified as a CoP: the domain, community, and practice. Members of a CoP share an identity with a domain of interests (e.g., phosphorus sustainability), have a community where members of the domain interact and engage with each other through shared activities or shared information (e.g., publishing research articles on phosphorus sustainability), and practice together through sharing a collection of resources (e.g., stories, tools, knowledge, and experiences) that the community develops together (Wenger, 1998). CoP provides novice members of the community to become experienced members through practice and apprenticeships with more knowledgeable experts in the domain (Lave & Wenger, 1991; Polizzi et al., 2021).

Phosphorus sustainability education has the potential to benefit from the development of CoPs. CoP can allow sustainability researchers and science education communities to collaborate and share ideas, resources, and challenges associated with sustainability education (Hestness et al., 2014). This research study utilizes the knowledge and expertise of researchers who are actively involved in the phosphorus research community to provide the education community the opportunity to become informed on salient issues of phosphorus sustainability and improve phosphorus sustainability literacy.

Methodology

Qualitative interviews were conducted with researchers who study phosphorus sustainability. The researchers' knowledge of phosphorus sustainability was utilized to inform and guide future educational efforts on the topic for formal (e.g., K-12 schools, colleges, and universities) and non-formal (e.g., extension agencies, museums, and science centers) learning environments.

Participants

Potential participants were recruited from phosphorus sustainability organizations (e.g., Science and Technologies for Phosphorus Sustainability [STEPS]) and authors of published phosphorus literature through email invitations. Published literature included journal articles and reports (e.g., Our Phosphorus Future Report; Brownlie et al., 2022). Snowball sampling, a recruitment technique where participants are asked to recommend other potential subjects (Creswell & Poth, 2017), was also used to recruit participants for the study.

Because sustainability involves knowledge from multiple fields (Annan-Diab & Molinari, 2017), purposeful sampling was used to select researchers from science, engineering, social science, and/or policy fields. All participants who accepted the email invitation were interviewed. Twenty participants (see Table 3.1 for demographics) were interviewed; twelve had expertise in multiple professional fields. Participants had disciplinary backgrounds in engineering (n=6), science (n=11), and social science or policy (n=10; see Table 3.2). On average, participants had 6-10 years of experience working in phosphorus sustainability.

Table 3.1

*Participants' Demographics (*N = *49)*

Demographic	n	%
Gender		
Man	10	50
Woman	10	50
Ethnicity [a]		
Hispanic, Latinx, or Spanish	1	5
White	20	100
Age (in years)		
31-40	6	30
41-50	7	35
51-60	1	5
61-70	5	25
Prefer Not to Disclose	1	5

[a] Total sample adds over 100% because one participant identified as mixed (one person identified as Hispanic and White).

Table 3.2

*Participants' Expertise and Years of Experience (*N = *49)*

Expertise and Years of Experience	n	%
Professional Group [a]		
Engineering	6	30
Science	11	55
Social Sciences and Public Policy	10	50
Years of Experience in Primary Disciplinary Fields of Expertise		
6-10	3	15
11-15	7	35
16-20	4	200
More than 20	6	30
Years of Experience in Additional Disciplinary Fields of Expertise[b]		
6-10	3	15
11-15	4	20
16-20	2	10
More than 20	2	10
Years of Experience Studying Phosphorus Sustainability		
1-2	2	10
3-5	6	30
6-10	5	25
11-15	2	10
16-20	3	15
More than 20	2	10

[a] Total sample adds up to over 100% because 12 participants reported having an additional disciplinary field of expertise, so some participants are included in two professional groups.

[b] Only 12 participants reported having an additional disciplinary field of expertise, so the total does not add up to 100%. One participant reported having an additional disciplinary field but did not report how many years of experience they had, so results are shown for only 11 participants.

Interview Protocol

Semi-structured interviews were used to capture participants' insight on phosphorus sustainability education. The protocol was reviewed by a panel of stakeholders, including two educational researchers and two phosphorus sustainability researchers. Two phosphorus sustainability postdoctoral scholars also piloted the interview protocol. Revisions to the protocol were made based on feedback from the stakeholder panel and pilot participants and included modifications for clarity and language.

The 17-question interview protocol (see Appendix D) took participants approximately 45 minutes to complete. Interview questions covered a variety of topics and were split into three sub-sections: *Participant Background with Phosphorus Sustainability, Conceptualization of Phosphorus Sustainability,* and *Phosphorus Sustainability Education*. The first sub-section, *Participant Background with Phosphorus Sustainability*, contained three questions covering the participants' disciplinary background and history working with phosphorus sustainability (e.g., "*How did you get involved in phosphorus sustainability?*"). The second sub-section, *Conceptualization of Phosphorus Sustainability*, consisted of six questions. These questions strived to capture participants' insights and opinions on phosphorus sustainability (e.g., "*How is phosphorus sustainability different from other types of sustainable development challenges?*"). The last sub-section, *Phosphorus Sustainability Education*, contained eight questions regarding the who, what, where, and how of providing phosphorus sustainability education (e.g., "*What are the educational challenges for teaching and learning about phosphorus sustainability?*").

Data Analysis

Interviews were recorded through the online video platform Zoom, transcribed using Otter.ai, and checked for accuracy. Transcribed interviews were uploaded into Atlas.ti 24 for

qualitative analysis. The primary researcher opened-coded a sample of six transcripts for data themes. This inductive coding process continued until the emergence of new themes stopped occurring. Next, a codebook of 27 codes and descriptions (see Appendix E) was developed from data themes generated during the inductive coding process. A second coder, with experience in science education research and the field of phosphorus sustainability, was trained with the codebook to obtain inter-rater reliability. The two coders independently coded 20% of the same interviews and obtained an acceptable level of agreement with a Krippendorf alpha of 0.90 (Krippendorff, 2011). After obtaining inter-rater agreement, the primary researcher independently coded the remaining transcripts. Coding outputs were generated and analyzed by themes.

Results

Participants' Experiences with Phosphorus Sustainability

The twenty researchers who participated in this qualitative study encompassed a mix of different disciplines across the fields of science, engineering, and social sciences (e.g., limnology, environmental engineering, nutrient sustainability, natural resource economics, rural sociology). A majority of the participants mentioned becoming involved in phosphorus sustainability through opportunities offered to them during their graduate or post-doctoral studies. Another common reason for becoming involved in research on this topic was personal interest in topics related to phosphorus sustainability. As described by Participant 9:

> I skipped school, and I would go to the library. So, on this particular day, I found the Life Magazine, and it had a picture of a dead carp floating on it and it was called Blind in Great Lakes. That article contained a lot about water pollution of the Great Lakes, which are really special to Midwesterners, where I'm from. I had no idea there was anything

> called pollution. In those days, it was just not talked about with education at all. So it was at that point when I was 16 years old that I chose this profession, and the profession was to try to help control algal blooms through control of phosphorus and nitrogen in surface waters.

Other participants became involved with phosphorus sustainability later in their professional careers when they were invited to participate in a transdisciplinary collaborative project (e.g., a research center or an in-depth report) on the topic.

Participants' Views of Phosphorus Sustainability

Participants were asked to describe what phosphorus sustainability looks like. Responses included six themes and three sub-themes (see Table 3.3). The most common themes among the researchers were the environment and agriculture/food. Thirteen (65%) of the researchers included the concept of agriculture or food in their description of phosphorus sustainability. These descriptions included statements addressing the need for phosphorus in agriculture production to feed the world or maintain food security. Environmental protection was also included in thirteen (65%) researchers' responses. Researchers emphasized the need to use phosphorus in a way that is "friendly" towards the environment and minimizes the amount "lost" to the environment to reduce the environmental effects of too much phosphorus. Eleven (55%) researchers specifically emphasized the connection between lakes, rivers, or oceans' water quality and phosphorus usage within this environmental theme. Participant 5 stated, "It involves a common understanding across stakeholders of what the problems are with phosphorus in terms of its impact on water and what the solutions are."

Table 3.3

Themes and Sub-themes Researchers Associate with Phosphorus Sustainability

Themes and Sub-Themes		
Agriculture/Food	Equity [b]	Solutions
Economics	Politics [b]	Waste
Environment	Society	Water Quality [a]

[a] Sub-theme of environment.

[b] Sub-theme of society.

Other themes in participants' conceptual descriptions of phosphorus sustainability included economics, solutions, waste, and society. Eight (40%) researchers highlighted the need to consider the economic interests associated with phosphorus sustainability. Some researchers elaborated on how economic interests can conflict with environmental interests and that both need to be balanced. Nine (30%) participants discussed the variety of available solutions or ones that need to be developed to assist in using phosphorus more efficiently. Examples included changing human diets (e.g., eating less meat) and recycling phosphorus from waste systems. Six (30%) responses addressed sources of waste (e.g., human, food, manure) when describing phosphorus sustainability. In addition, six (30%) responses emphasized the societal needs and impacts of phosphorus sustainability. Within this societal theme, the sub-themes of equity and politics appeared in participants' descriptions. Three (15%) participants mentioned equitable access to phosphorus and food, and three (15%) mentioned the political factors associated with this topic. Participant 3's description of what phosphorus sustainability looks like demonstrates several of the themes described above:

> I would say it is the sustainable use of phosphorus within the anthropogenic phosphorus cycle to minimize environmental harm, maximize agricultural output and efficiency, and

> empower social equality and communities. The important thing here is that there is a food security component, a water pollution component, and a social equality or equity component, and phosphorus sustainability is about bringing all those together. In some ways, it's too much phosphorus is a problem or too little phosphorus is a problem. Getting phosphorus to the right kind of people is the solution.

Conceptual Changes

Participants were asked to share how their view of phosphorus sustainability has conceptually changed throughout their careers. Almost all the responses discussed how their view of phosphorus sustainability changed from a narrow focus on just one or two parts of the phosphorus problem to gaining a bigger appreciation and understanding of various components of the phosphorus sustainability challenge. At the beginning of their careers, several researchers stated they initially only thought of the environmental impacts of phosphorus (e.g., water quality); however, they now have a broader and holistic perspective of phosphorus sustainability where they consider additional factors and implications (e.g., economics, importance for food production, social equity challenges). Specifically, six (30%) participants explained how they better understand the political influences and political role in developing phosphorus management policies. Participant 3 stated:

> It takes a while to grasp. There is the concept that it's not a complex issue, but there's lots of complexity in there. The biggest change to me throughout my career is the social side of things. There's injustices around phosphorus sustainability that upset me that I want to correct. And I see that there is political involvement. That's difficult. And much as any other big industry, there's industrial influence, which is potentially looking at building economic wealth as opposed to serving the people."

Six (30%) of the researchers were unaware of this issue when they first became involved with phosphorus sustainability. However, this has changed as they have gained awareness and knowledge of this topic. As described by Participant 5, “To be honest, before I started working on phosphorus, I didn’t know a terrible amount about it [phosphorus sustainability], so there’s definitely been a shift there. It’s something I’m very aware of now.”

Unique Traits

Phosphorus sustainability is one of many different types of sustainability challenges. Participants were asked to share what they saw as “unique traits” distinguishing phosphorus sustainability from other challenges (e.g., climate change, drinking water, energy). Eight (40%) participants described how this essential nutrient, which is necessary for life, has no alternative substitutes, while other sustainability challenges involving fossil fuels, like sustainable energy and climate change, have a variety of alternative energy sources that can replace fossil fuels. As described by Participant 15, “Humans existed for 1000s of years before oil, electricity, and coal, but humanity and life did not exist pre-phosphorus.” Seven (35%) participants emphasized the lack of awareness among society regarding the topic as being unique from other environmental challenges. For example, Participant 6 said, “We don’t get a lot of press coverage. It’s really hard to compete with, you know, these poster children of case studies like climate change.”

The geographic distribution of phosphorus and, subsequently, geopolitical complications were mentioned by five (25%) participants. These researchers acknowledge that other challenges (e.g., fossil fuels, water) share similar geographical and geopolitical issues; however, phosphorus reserves (e.g., phosphate mines) are less abundant than oil, coal, and water reserves. This makes resolving these issues associated with phosphorus sustainability potentially more challenging. Phosphorus sustainability challenges were also described as being more abstract by three (15%)

researchers. Unlike climate change, where people can see or witness the impacts of a growing global temperature, the general public does not always notice or are unaware that issues they see in the environment are related to phosphorus levels in the environment. As seen in Participant 6 statement, “It’s hard to connect the green slime and algae blooms with upstream pollution [to phosphorus].”

Other traits that were mentioned include the lack of policy, both locally and globally, surrounding phosphorus compared to other challenges like climate change and energy, and that unlike other biogeochemical nutrients (e.g., water, carbon, nitrogen), phosphorus does not have a gaseous phase to its cycle. Participant 17 stated:

> One major difference in phosphorus is that, unlike carbon, nitrogen, and water, there is no gaseous form of phosphorus in the normal cycle. That’s why it is both a global issue and primarily a local issue because wherever you use it, it ends up locally.

Several participants provided some “positive” traits they associate with this challenge that other challenges do not have. For example, two participants mentioned that phosphorus sustainability is easier to solve than other sustainability challenges. Participant 16 stated:

> In many ways, I think phosphorus is a lot easier to deal with than some of the other ones. It is a finite resource that doesn’t have a gaseous phase. We can understand the flows and where they’re going a bit easier. And because by nature, phosphorus only exists in certain places, geographically in terms of economically feasible minings, there are easily identifiable levers. The main industrial uses of phosphorus are not incredibly diverse. You know most of it is going towards fertilizers. So that also simplifies things versus like the energy sectors. There are so many different pieces to that pie that even if you do a really good job in one, you’re not necessarily going to see vast improvements. I also

> think phosphorus sustainability doesn't have the PR [referring to public relations] challenges that some of the other areas do, like climate change. Most people don't know what it is. And so they might be more open-minded in thinking about sustainable approaches.

Root Causes of Phosphorus Sustainability Issues

Participants were asked to explain what they view as the "root causes" of unsustainable phosphorus development. The two major themes across participants' responses were economics and agriculture practices. Sixteen (80%) researchers reported economic-related factors. One common sub-theme was the inexpensive cost of phosphorus for commercial purposes. Researchers discussed how the low price of phosphorus provides no economic incentive to conserve it, which leads to over-consumption. Additionally, overconsumption continues because the total cost (e.g., environmental cost, government subsidies) has been left out of the economic pricing of fertilizers and other phosphorus-containing products. Capitalism was another sub-theme commonly mentioned by participants. Participants emphasized how capitalistic views and practices encourage the philosophy of producing, selling, and consuming as many products as possible, leading to overconsuming phosphorus in many parts of the world (e.g., developed countries, the Global North). As described by Participant 17:

> It's a consumer-driven society that assumes unlimited resources. Especially in the last 50 years, our society has not really been limited, at least in any long-term, meaningful way. There have been no serious limitations on our resources for most of the developed world, so we have acted accordingly. If there is no limit, there's little value to how we consume things. It's a matter of convenience, and we prioritize that instead of sustainability.

In contrast, they also mentioned that parts of the world (e.g., developing countries, the Global South) still have little to no access to phosphorus, and geopolitics driven by capitalism make access to phosphorus volatile. Some participants mentioned the marketing by fertilizer companies has led to the spread of misinformation that adding extra phosphorus to your plants will lead to better blooms and yields. Other participants shared how "big businesses" influence has also led to a lack of political priority and will to take action from a policy standpoint of managing and regulating phosphorus.

Nine (45%) participants reported agriculture practices underlie phosphorus sustainability challenges. One sub-theme was the lack of awareness and understanding of current best fertilizer practices by farmers which is leading to overconsumption. For example, Participant 18 stated, "We're not using variable rate application to match the application rate to the soil requirements and the crop needs. It's being used in a very wasteful manner, and it's been over-applied in a lot of cases." Participants emphasized how farmers have not received quality guidance on when to apply phosphorus-enriched fertilizers and how much to use. In addition, they mentioned how there is a disconnect with some farmers around the idea that more phosphorus does not necessarily equate to higher yields. Participants acknowledged that plants need phosphorus to grow, but the total amount required is relatively low, and farmers continuously apply more phosphorus than is needed.

Another agricultural issue that was raised was that when the fertilizer industry was initially developed, most of the world's agricultural soils were extremely poor in nutrients, especially phosphorus, so application recommendations were based on soils deficient in nutrients. Over several decades of fertilizer applications, essential nutrients, like phosphorus, have built back up in the soil; however, recommended fertilizer practices have not been adjusted

to match the needs of current soil nutrients. Lastly, several participants mentioned society's disconnect between economic and environmental interests as another fundamental cause behind phosphorus sustainability challenges. Researchers described how most of society does not associate their consumption of phosphorus with the ecological problems affecting ecosystems (e.g., eutrophication of surface waters).

Educational Guidance For Teaching the Root Causes of Phosphorus Sustainability Issues. All twenty (100%) of the participants agreed that it is important for educators to address these fundamental issues with students or audiences when teaching phosphorus sustainability. One reason stated by researchers is that in order to prepare people to implement or develop the appropriate solutions that lead to the sustainable use of phosphorus, they need to understand what is causing the problem in the first place and be aware of the connections between the economic and environmental systems. This is seen in Participant 18's response,

> I think there's a need for greater awareness of that [referring to root causes], especially on the front end of any student project that involves some kind of nutrition or fertility aspect. I think there needs to be an education component where they're learning about the inputs related to phosphorus, how those are being misapplied, and some of the environmental impacts of their production and application.

Researchers emphasized that while it is important to address these fundamental issues, they also stressed that the context for presenting them is also important. It was recommended that the root causes be presented in a way that would connect with students and audiences. Participants noted that educators need to make it relevant to their students or audiences by exposing them to why it is important and how it impacts them.

Consequences of Maintaining the Status Quo

Participants listed two main consequences for not achieving phosphorus sustainability: increased environmental damage and food security risks. The most frequently mentioned consequence by researchers was increased environmental damage, with seventeen (85%) researchers including it in their responses. Environmental damages included increased soil and water quality degradation. The researchers expect more surface waters to be impacted by eutrophication events, affecting not only the biodiversity of these aquatic ecosystems but also public health, access to safe drinking water, and businesses (e.g., tourism and fishery industries) that utilize surface waters. Referring to the negative impacts eutrophic events have on local economies, Participant 19 said, "It's millions and millions of dollars of damage to the economy annually." Researchers also highlighted the connections between algal blooms caused by phosphorus and climate change. Another consequence of eutrophic events occurring more frequently is the large amounts of greenhouse gases (e.g., methane, nitrous oxide, and carbon dioxide) released during these events, warming the planet and making it easier for lakes to become eutrophic. Participants also emphasized that it is technologically easier and less expensive to prevent the eutrophication of surface waters than to remediate it after it occurs:

> It takes a lot more energy to turn them back. You can't just remove that extra little bit of phosphorus you just added. You have to go back to a much lower point. The worst-case scenario if nothing happens [referring to phosphorus sustainability] is you're going to get to a point where lakes all around the planet start getting these algae blooms, which we just don't have the resources, the infrastructure, the finances, political will, or public support to deal with. It's hugely expensive (Participant 3).

Growing food security risks were included in ten (50%) of the participants' responses as consequences of not achieving phosphorus sustainability. One factor leading to food insecurity will be the rising cost of fertilizers as accessible phosphate from mines becomes less readily available. Six (30%) of the researchers discussed the increasing cost of fertilizers and food as the main culprit to food insecurity. Several researchers also addressed issues of social equity related to food insecurity and mentioned how food insecurity will affect already marginalized populations first. For example, Participant 17 stated:

> Phosphorus will become more expensive. Because phosphorus is required to fertilize the crops that we eat, our food will become more expensive. It'll start as most things do in the less developed world. There will be food shortages and the societal upheavals that come with that.

In addition to social equity issues, researchers mentioned increased geopolitical conflicts as the supply from phosphate mines diminishes and countries have fewer choices for buying phosphate.

Educational Guidance to Avoiding "Doom and Gloom." Participants provided educators recommendations for avoiding feelings of "doom and gloom" when teaching students or audiences about the consequences of not addressing phosphorus sustainability. The most frequently suggested strategy for communication phosphate issues is to focus on the solutions that are either available or can be implemented by the students or audience. Addressing phosphorus sustainability solutions, such as eating less meat or recycling phosphorus from waste, was suggested by the majority (65%) of the participants. Participant 5 reported:

> It's really important to talk about solutions. We've got lots of solutions on the table. It isn't necessarily a question that we don't have the means. You've got to be able to show

> people what can be done about this. This is a solvable problem that we can address; there isn't a technological obstacle to it.

In conjunction with educating on the solutions to phosphorus sustainability, ten (50%) of the researchers emphasized empowering students and audiences to take action to avoid feelings of "doom and gloom." Researchers stated it is important to inform the audience they have the power and ability to influence changes toward phosphorus sustainability. For example,

> Policies got us where we are; policies can get us out of here. This [referring to the phosphorus sustainability challenge] is not anything where we don't have agency and capability for change. You have to tell students we do have agency and we can change the way we're doing things. I think being informed and understanding the room for action that exists, you know, is actually quite empowering (Participant 4).

Actions that students and audiences can be empowered to take include their consumer purchases, voting for politicians who support pro-phosphorus sustainability policies, and contacting elected officials demanding they take action. This theme of empowerment was noted by Participant 2's statement:

> You have your hat as a consumer and what you eat, you have a hat as a parent, and you have a hat as a citizen. And I think we're in a little bit of a democracy crisis in a lot of parts of the world because a lot of these issues need to do with collective action. When teaching about these issues, it's about empowering people to say, 'You do have power in so many ways, not just about what you put on your plate, it's about whether you are going to be lobbying your sitting government to have compost? Are you asking questions about whether that [compost] will be used in farming versus landscaping? I also try to

> often talk about how not doing something is a choice and action, and the status quo is a choice we can choose to leave.

Educational Priorities for the General Population and Students

A lack of awareness of the phosphorus sustainability challenge in society was frequently mentioned throughout participant interviews. Participants emphasized one of the main priorities for educating the general population is for them to have a broad and basic understanding of the phosphorus system. This broad understanding encompasses what phosphorus is, why it is important, how it circulates (e.g., runoff, waste), and its negative impacts. Several researchers mentioned that it is important for the general public to distinguish that too much phosphorus can have adverse effects, but phosphorus itself is not bad and is important for sustaining life. Participant 2 stated:

> I think it's really important they understand that it's not a pollutant or something you always need. It's both at the same time. In order to have water quality and food security at the same time, we need to be managing in a way that addresses both.

A basic understanding of phosphorus sustainability was recommended for the general population because most adults already have a lot of other things they are worried about or have been told they need to care about. As seen in Participant 8's response, "The average adult is pretty maxed out. [in reference to things they need to care about]."

In addition to raising basic awareness around phosphorus sustainability, it was also recommended that another educational priority for the general public should be solutions and actions they, as individuals, can implement. Participants argued that these solutions and actions should resonate with topics the audience would find important or interesting, "I would try to gravitate towards the issues that will make a difference in their lives by telling them how

important it is" (Participant 9). Topics suggested included phosphorus impacts on their health, access to safe drinking water, their influence as consumers with diet choices, food waste, and food security. Food waste, choice, and security were the most frequently suggested topics that would resonate with people, appearing in ten (50%) participant interviews.

Regarding the educational priorities for students, participants stated they would include everything they recommended for the general population but expand further on the nuanced details. A common theme among participants was educating students with more information and specifics than they would with the general population. Participant 8 said, "I think, among students it is a really interesting topic. I think they enjoy the complexity and thinking about things from a technical, social, and geographical perspective." Other concepts that participants suggested for students included current challenges researchers face with phosphorus sustainability, technological solutions to mitigate or solve challenges, mass balances, inputs and outputs of the phosphorus system (e.g., how the food humans consume ends up at wastewater treatment plants), and the benefits and threats of food production. Specific skills, such as communication, critical thinking, and systems thinking, were also recommended as a priority for students to learn.

Developing systems thinking skills in students to approach learning phosphorus sustainability appeared as a priority in eight (40%) of the interviews. These participants discussed the importance of students approaching phosphorus sustainability from a holistic perspective, where they are factoring in the different sub-systems (e.g., agriculture, waste) involved, humanity's impacts, and the mechanisms for addressing phosphorus sustainability. For example, Participant 2 stated:

> It always ends up coming back to systems thinking. We have siloed thinking, and while some teachers are trying to move away from it, education is still siloed. In order to address this challenge, you have to have a common understanding of how systems work and how they're interlinked. Humans are not like economic models; they have complex lives and multiple reasons for making the decisions that they do.

In conjunction with systems thinking, developing interdisciplinary knowledge and skills also appeared as a priority for educating students. Five (25%) of the researchers discussed the need for students to approach learning phosphorus sustainability from different disciplinary perspectives, "Interdisciplinarity is key; you can't really get the hang of this without having an interdisciplinary approach" (Participant 12). It was also suggested students be prepared to communicate and collaborate because current challenges require the collaboration of people from different expert backgrounds, "While you may be trained in a certain discipline, you need to be able to work with others and understand how others think" (Participant 6).

When discussing preparing students for interdisciplinary learning on phosphorus, social science skills and knowledge were explicitly called to attention as necessary for students to learn to address current phosphorus sustainability challenges. Researchers shared how science and engineering solutions can only get 'us' so far because phosphorus sustainability is rooted in societal behavior and governance issues. As seen in Participant 4's statement:

> We should prepare students for solutions that are not tech-based. I think that a lot of the people who play a big role in this kind of space are people who are STEM-trained. They are, by training, very pro-tech in the solutions they propose…I think that lack of humility and understanding of policy factors, political issues, and cultural issues becomes a

> deterrent. So I think these two things are where the new generation of scholars who are going to work on issues of sustainability need to be trained better on.

When discussing the challenge of empowering people to take positive action towards phosphorus sustainability and implementing solutions, participants recommended that the next generation of students be trained to think creatively and apply that creativity to develop impactful messaging to get people to care. Participant 3 shared:

> We need the next generation to be really good at communicating. That means skills in graphic design and how to psychologically and emotionally engage people. The next generation must make the messaging powerful and use good fonts, color palettes, and branding. We need to be sophisticated and intelligent. Working with graphic designers and PR execs. That's what I would like to teach.

When teaching phosphorus sustainability to a public audience or students, researchers provided a variety of historical events they recommended addressing. Some of these events were the historical use of phosphorus pre-commercial fertilizers (e.g., bone meal, manure, and guano deposits). These historical events show that humans have always been aware of phosphorus's critical role in agriculture and that geopolitical disputes have occurred over this essential nutrient for centuries. Participant 5 stated, "We need that history of exploitation and extraction, so we understand the inequalities within that system so that we don't repeat that when we try to create a sustainable system and can build equity into our solutions." Past eutrophic events, like the 2014 Toledo water crisis, where a large eutrophic event occurred in Lake Erie and the city of Toledo's water supplies became unsafe to drink and use, were also suggested as cases to be shared with audiences or students. Other events mentioned by participants included the historical impacts of

the Green Revolution and the volatile fluctuations of fertilizer and food prices over the past twenty years.

Educational Challenges for Teaching and Learning Phosphorus Sustainability

Participants provided four main challenges one could experience when teaching or learning phosphorus sustainability. Eight (40%) participants mentioned that the complexity of phosphorus sustainability makes it difficult to learn and teach. Participants also discussed that phosphorus sustainability involves many disciplines, so having a cohesive understanding of the topic requires knowledge of different disciplinary fields. Four (20%) participants raised concerns about where phosphorus sustainability will fit in educational curricula. Most education systems teach in disciplines, making it potentially challenging to include intradisciplinary topics. One participant shared:

> There's a lot of disciplines involved. Unless you have a system that permits you to bring together a lot of different perspectives at once and spend enough time on them to convey what's going on, you're gonna have a hard time doing that because, in high school or grade school, you've gotta be teaching to the standards (Participant 10).

Another curriculum challenge elaborated by participants is finding time and space to incorporate phosphorus sustainability into the curriculum, which is already maxed out with other important content. Additionally, some of the disciplinary topics associated with phosphorus sustainability can be complex and challenging to understand (e.g., chemistry).

Seven (35%) participants shared challenges regarding getting people to care about phosphorus sustainability. Participants mentioned how there are many environmental challenges people have been educated to care about and take action on (e.g., climate change, water conservation, recycling). They expressed concern about how adding another issue to care about

could send people past their mental capacity to care, “The other challenge is there’s a lot of environmental problems going on. There’s only so much room and bandwidth for people to take on environmental problems” (Participant 3). The disconnect between the negative impacts of phosphorus and people can also make it challenging to care enough to encourage pro-environmental behavior. Unless a person has experienced an algal bloom, most of society has not seen the detrimental effects of unsustainable phosphorus consumption. As one participant stated, “It’s probably harder for people to care about an environmental problem that’s not happening in their own backyards” (Participant 7). There are a lot of stakeholders involved in phosphorus; it was also emphasized that certain stakeholder members could feel polarized if blame or shame is given to a stakeholder group (e.g., students who come from farming families), which could cause them to shut down or not participate in the learning conversation.

Lastly, censorship concerns were raised by three (15%) researchers. Participants stated how lobbying by fertilizer companies and other economically invested stakeholders could make teaching this topic difficult. It was suggested the political and economic interests associated with phosphorus might cause some educators to self-censor out of fear of losing their jobs or being forced by their employer to censor their educational messages regarding phosphorus (e.g., not being allowed to tell students that agricultural fields are the main source of phosphorus runoff). Participant 9 shared, “It’s not the teaching that’s difficult. It’s teaching why it is critically important to people’s health and well-being because it starts to cross into issues of policy and politics, and that’s what is controlling education.”

Role Educators Can Play in Affecting Change

Educators could potentially make an impact on changing human practices and phosphorus consumption by incorporating the topic into their lessons. It was suggested that

educators have the opportunity to be leaders in phosphorus sustainability by advocating for the subject to be included in courses. As one participant stated, “I think people [educators] can raise awareness by using it [in lessons]. I think it’s a great example to show a lot of issues” (Participant 2). Educators also have the opportunity to emphasize specific solutions (e.g., diet changes) and allow students to analyze the pros and cons of alternative solutions. Educators have a unique opportunity to provide broader context and significance to phosphorus sustainability, making the topic more accessible to learners.

Educational Recommendations for Teaching and Learning Phosphorus Sustainability

Phosphorus sustainability impacts people from all walks of life, and participants shared a variety of different recommendations to engage audiences across different generations, cultures, places, and disciplines. Fourteen (70%) participants suggested educators tailor their content to address the personal interests of their students or audience. While people might have specific things they find important (e.g., farmers caring about crop yields), participants provided three topics they believe would be universally important to everyone: food, safe drinking water, and personal health for themselves and their families. Participant 4 said:

> I teach this big intro class that has 400 students in it. The thing that gets them all interested is food. Talking about changing your diets, where your food comes from, or thinking about the land use applications of diets because we all eat. I think it’s something where people can really see the connection between both their individual action and collective action.

Other recommendations included providing multiple avenues for people to participate in open discussion (e.g., chat boxes, think-pair-share opportunities) and encouraging humility and respect for other people’s perspectives and experiences. A few participants recommended

utilizing creative mediums like art, documentaries, or musicals (e.g., the Broadway musical Urine Town) to engage people from different backgrounds. Participant 10 provided an example of how an art exhibition facilitated conversation around phosphorus sustainability:

> I know that when we had the sustainable phosphorus summit a few years ago, one of the most successful things about that meeting was an art exhibition during the conference. Artists were recruited and paired up with scientists and others who work in phosphorus sustainability. Then there was art produced, and then there was an exhibition, and it was pretty fun. That started a lot of conversations.

Adapting Phosphorus Sustainability into Curriculum

Participants were asked to share how educators can incorporate phosphorus sustainability into their teaching. The most frequently recommended suggestion was to use phosphorus as an example or "learning tool" when teaching standard course content. Ten (50%) of the participant's responses included this theme. Participants described how creating whole new units, specifically on phosphorus, is unnecessary. They suggested that there are many topics taught to students (e.g., climate change, nutrient cycles, natural resources, mining, water quality) where phosphorus sustainability can be incorporated. For example, one participant suggested phosphorus can be introduced in high school chemistry classes when students learn stoichiometry. Students will learn from doing stoichiometry calculations that elements, such as phosphorus, are not created or destroyed during chemical reactions; they are just rearranged. Other suggestions from participants included educators collaborating with phosphorus sustainability experts to assist with developing case studies, practice problems, and quiz or test questions that include phosphorus but also align with the standards teachers are required to teach. Participant 13 shared,

> Figure out how you [referring to researchers who study phosphorus sustainability] can start to introduce adding a new problem that's all focused on phosphorus would be a great initial step. Working with the educators that have to teach certain core requirements and say, 'How can I help you include a couple of new problems, quiz questions, or case studies that connect to phosphorus sustainability.' I went on a wastewater treatment field trip with K through 12 teachers this past summer. One teacher emailed me afterward asking for help developing a problem. We had a few email exchanges; it didn't take me much time, and now this person has a whole new problem. It's still checking the core that he has to teach, but now, there are integrated elements of nutrients, wastewater treatment, and microbiology all in there. My thought is sprinkling some of those throughout classes, through the K through 12 levels, as a way to start.

Another theme that appeared throughout seven (35%) of the participants' interviews was providing interdisciplinary learning opportunities for students by incorporating phosphorus sustainability lessons outside standard science classes (e.g., biology, earth science, chemistry, and physics). Participant 11 stated, "Teaching it all together in a systemic way instead of a siloed way would save us time and enhance the systemic understanding [of phosphorus sustainability]." Suggested courses included international relations, math, social studies/history, geography, and economics. One participant recommended "a phosphorus week" (Participant 8), where students could learn about the different components of phosphorus sustainability (e.g., the chemistry of phosphorus, prices of fertilizers, global distribution of phosphorus, and technological recovery methods) throughout their different disciplinary courses.

Impactful Learning Experiences

Participants provided a variety of experiential learning activities that would be important for learning phosphorus sustainability. Field trips to wastewater treatment plants, eutrophic surface waters, and farms were the most frequently suggested activities. Eight (40%) participants described how visiting wastewater treatment plants would be engaging for students, "I think wastewater really stands out because of the focus at the facilities on removing phosphorus. You can have a very long discussion with people about phosphorus because it's so important to them [referring to wastewater treatment employees]" (Participant 13). Facilities related to food waste, such as landfills and composting facilities, were also recommended as possible field trips.

Seven (35%) participants said that bringing people to visit surface waters affected by eutrophication to witness the ecological disruption caused by phosphorus runoff would be impactful for learning phosphorus sustainability. Participant 19 shared:

> Once students can actually see firsthand some of the turmoil from these algae, that can make a big difference. I remember it changed my perspective flying over Lake Erie one time and seeing these algae blooms from above. It totally puts them [eutrophic surface waters] in a different perspective. I think those experiences are what are going to stick with students.

Additional activities that were suggested while visiting surface waters included doing infield water sample testing and comparing the results from eutrophic and non-eutrophic water bodies, "It can be really exciting and interesting for students. They [students] really like sampling and understanding where data comes from" (Participant 2). Six (30%) participants recommended taking students to farms or providing students opportunities to engage with farmers (e.g., guest

speakers) to develop a deeper understanding of phosphorus sustainability. As seen in Participant 14's statement:

> I've worked with a few programs that connected students with farmers, and they had an opportunity to visit farms and see firsthand the different forms of management being applied. The more you can get those kinds of connections started, the more you can get an effective education.

In addition to field trips, participants provided a variety of classroom and lab-based activities that educators could use with students. Examples included performing experiments where you observe the effects different levels of phosphorus exposure have on plant growth, nutrient bioassays, column leaching experiments, collecting pH soil samples or water samples, and watershed models. One participant suggested developing case studies, "Case studies are always great when you start diving into a mass balance of phosphorus in a city or an agriculture field" (Participant 16). Another suggestion was a citizen science project involving people collecting water samples would assist with building connections between the effects of weather, temperature, precipitation, and runoff on phosphorus levels and water quality. A non-science-specific example that was shared was conducting a model UN [United Nations] or youth government activity centered around the challenges of phosphorus sustainability where students can role-play representing different stakeholder groups. As described by Participant 16:

> Rather than representing countries like India or the UK, you're [students] representing farmers, wastewater treatment plant operators, synthetic fertilizer companies, and then building out some kind of collaborative governance discussion where people are taking on the roles of these folks and getting them to a place where they realize how difficult it

is to come to an agreement on all sides and to think about the second or third order consequences of what that agreement might look like.

Discussion

Expert knowledge has previously been used to develop instructional materials to improve learning (Poureslami et al., 2017; Catrambone, 2011; Thomson et al., 2019; Trujillo et al., 2016). This study employed the expertise and experiences of researchers who study phosphorus sustainability to provide guidance and recommendations for teaching and learning phosphorus sustainability. Drawing from their personal experiences, participants' interviews delineated the traits, concepts, and skills that comprise phosphorus sustainability, giving the educational community a framework for phosphorus sustainability education. Participants in this study shared the challenges associated with teaching and learning about phosphorus sustainability and provided suggestions on managing and overcoming these challenges.

Participants consistently mentioned a general lack of awareness about the phosphorus sustainability challenge facing the world. In order to avoid the negative impacts of the unsustainable management and consumption of phosphorus, we need to make society aware and motivated to implement effective sustainable solutions (e.g., behavioral changes and technological advances). Through education, we can raise social welfare concerns among individuals and increase pro-environmental behavior (Meyer, 2015). As seen with other sustainable challenges (Cordero et al., 2020; Jalil et al., 2023), increases in pro-environmental actions among society can potentially work to promote phosphorus sustainability through education; however, the messaging and strategies need careful consideration.

Participants from this study stressed that it is important for educators to refrain from promoting the idea that using phosphorus and having it present in the environment is a negative

condition. These researchers noted that phosphorus is a naturally occurring element in environments and is required for life. It is known that message framing of sustainable development challenges (e.g., renewable energy) can significantly impact individual attitudes and behaviors (van de Velde et al., 2010). Furthermore, it is important that educational content does not alienate important stakeholder members and communities like farmers and the agricultural industry. One benefit regarding the lack of awareness from the general public is that phosphorus sustainability currently does not have pre-existing public relations challenges like climate change (McKie & Galloway, 2007). The politicization of climate change among society has made climate change education difficult (Kersting, 2023). The educational community has the opportunity to use the knowledge and experiences gained from climate change and other sustainable challenges to design instruction that can mitigate the politicization of public opinion.

In addition to the environmental perspectives, social, political, and economic factors were frequently brought up by participants as factors influencing phosphorus sustainability; however, sustainability has a history of being framed with an environmental lens (Buchanan, 2012; Dyment & Hill, 2015). Research has shown that teachers and students have limited to moderate knowledge of sustainability. For example, a study of pre-service teachers' views of sustainability found that 59% of pre-service teachers mainly focus on environmental themes with little reference to other key components of sustainability (e.g., economic, social, political; Dyment & Hill, 2015). Other research has captured similar findings that teachers and students lack a holistic view of sustainability and familiarity with socio-economic aspects of sustainability (Sinakou et al., 2019). There is a critical need to provide pre-service training and professional development opportunities for in-service teachers that prepare them with the knowledge and skills to teach sustainability from an interdisciplinary perspective.

Concerns over siloed learning and technology-only focused solutions were raised in the results of this study. Despite evidence documenting that students' sustainability competencies improve when sustainability is presented from an interdisciplinary perspective (Walshe, 2017), schools have challenges teaching it outside of disciplinary frames (Moore, 2005). Sustainability encompasses a wide array of interconnected factors, often requiring knowledge from multiple disciplinary fields. This inherent complexity has been continuously documented by teachers as one of the main challenges for integrating sustainability education into their classrooms (Anastasiadis et al., 2021). The *Next Generation Science Standard's* definition of sustainability focuses on solving sustainable challenges through science and technology (National Research Council Lead States, 2013). This technology-centered perspective leaves out the important social and ethical dimensions of sustainability. Weeth and colleagues (2014) have called on schools to allow more opportunities for STEM educators (e.g., science teachers) to collaborate with non-STEM educators (e.g., social studies teachers) to provide students with a comprehensive education on sustainability. The prominence of standardized tests has also prohibited the integration of interdisciplinary learning in schools (Redman, 2013). The experience of researchers in this study suggests that through collaboration and intentional effort, phosphorus sustainability can be incorporated into classroom learning while still meeting course requirements.

Approaching sustainability education through a systems thinking approach has the potential to assist with the inherent complexity associated with sustainability. Systems thinking assists learners with making connections between the social, economic, and environmental factors associated with sustainability and observing sustainability with a holistic view (Molderez & Ceulemans, 2018; Shaked & Schechter, 2017); however, systems thinking is not regularly

integrated or developed in student learning at the higher, secondary, or primary education level (Gilissen et al., 2020; Kunz et al., 2017). This prior research is consistent with the challenges raised by participants in this study for teaching and learning phosphorus sustainability. If school environments are to provide quality phosphorus sustainability education, there needs to be increased attention to developing and supporting systems thinking and interdisciplinary opportunities for approaches to sustainable instruction.

Activities incorporating experiential learning, a derivative of constructivism (Bartle, 2015; Seaman, 2008), were recommended by study participants to assist with learning phosphorus sustainability. Even though participants in this study and prior research have stated that field trips (Kudo et al., 2021; Lin & Li, 2017) can be beneficial for learning sustainable development challenges, limited resources (e.g., financial and time) can make this an unrealistic reality for educators. Fortunately, participants recommended other experiential learning opportunities (e.g., case studies, lab experiments) that could be implemented more easily. Science education research supports active participation by students in case studies (Wei et al., 2018), lab experiments (Monroe et al., 2019), or discussions with stakeholder representatives (Noy et al., 2017) to assist with learning sustainability competencies and content knowledge. The phosphorus sustainability researchers in this study stressed these sustainability competencies that experiential learning fosters (e.g., critical thinking, systems thinking, collaboration, and empathy) as essential skills for the next generation of students to learn. It was also suggested that students could participate in a "phosphorus week," where they learn the different components of phosphorus sustainability in their classes throughout the week. Educators could use this approach as a framework to design a problem-based learning unit, which research has supported as being

an effective experiential learning strategy for sustainability education (Carrió Llach & Llerena Bastida, 2023; De Graff & Kolmos, 2003).

Incorporating creativity and art into phosphorus sustainability education was presented as an influential strategy for engaging learners in discussing, developing, and implementing phosphorus sustainability solutions in the results of this study. Aesthetic approaches can reinforce sustainability competencies with learners by allowing different perspectives and types of knowledge to be expressed (Heras, 2022; Lineberry & Wiek, 2016). The United Nations Educational Scientific and Cultural Organization (UNESCO) supports using art to advance sustainability education (UNESCO, 2023). UNESCO states that art and culture can be used as tools to evoke emotions and connect people to sustainability issues. Research in this area has documented students who were presented paintings during a lesson on sustainability found the paintings relevant because the paintings helped them better understand the meaning of systems thinking, how to think in patterns, and visualize how systems and environments are connected (Molderez & Ceulemans, 2018). In their study, art assisted students with self-reflection and opened their minds to alternative perspectives (Molderez & Ceulemans, 2018).

The results from this study suggest educators should situate their phosphorus sustainability educational message within topics that their audience (e.g., the general public, students) would personally connect with or find interesting. Participants' suggestions provided in this study included food, safe drinking water, and personal health because these impact people and their families directly. Kollmuss and Agyema (2002) reported feelings of environmental responsibility are shaped by what people prioritize and find important. In their study, participants reported that their personal and family's well-being was the most important to them and were their main priorities. Another study found similar findings, where participants reported not being

willing to engage in sustainable lifestyle changes unless they felt a direct personal relevance to it (Martin & Chen, 2016). Study participants identified with their work, family, and community (Martin & Chen, 2016). So, connecting work, family, and community to sustainability may be key to promoting pro-environmental behavior.

Conclusion

Unless we begin to take substantial action to mitigate the effects of humanity's past and current unsustainable phosphorus practices, there will likely be lasting consequences for water quality, food security, and international relations. The findings presented in this study can assist with the design and development of educational initiatives to increase the world's awareness of this sustainability challenge. The educational community can utilize the expertise provided by the participants in this study to develop and implement instruction and develop new curricula on phosphorus sustainability.

A limitation of this study is that the results are based on the perspectives and personal experiences of the researchers and may not be representative of researchers who study phosphorus more broadly. The educational recommendations provided by the participants have also not been assessed for their effectiveness in impacting one's understanding of phosphorus sustainability. However, many of the suggestions that emerged in this study have been shown to be effective with other sustainability topics. For example, several studies have documented the benefits of using art to learn about climate change (e.g., Bentz, 2020; Sommer et al., 2019) and integrating systems thinking to teach about water sustainability challenges (e.g., Powers et al., 2023). Regardless of the specific topic (e.g., climate change, energy, phosphorus), all sustainability challenges tend to be bounded by the competing interests of social, economic, and environmental factors. Therefore, there is promise in applying strategies used on other

sustainable topics to phosphorus. The next steps for phosphorus sustainability education will be taking the results from this study to develop educational materials that can be taught to students and audiences and then measuring the impacts lessons have on learners' pro-environmental behavior and general understanding and awareness of the topic.

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CHAPTER 4: Conclusion

This dissertation was a preliminary exploration of phosphorus sustainability education. It examined how phosphorus sustainability could be defined and conceptualized, presents suggestions for teaching and learning phosphorus sustainability and its potential challenges, and which skills and concepts to prioritize in curricula and lessons. Both studies utilized the expertise of phosphorus sustainability researchers as data sources. This chapter summarizes the research findings and implications from the preceding chapters. In addition, it discusses the dissertation's limitations and recommendations for future research.

Summary

Chapter 2

Chapter Two used the Delphi technique to survey 49 phosphorus sustainability researchers. The expert panel consisted of researchers from various science, engineering, social sciences, and policy disciplines. After three rounds of surveys and the attrition of 17 participants, 32 researchers agreed upon four big ideas (*circulating phosphorus*, *environmental pollution mitigation*, *healthy ecosystems*, and *sustaining and improving food production*) that are important to include when defining phosphorus sustainability and four big ideas that should be considered key concepts (e*nvironmental factors of phosphorus*, *food systems*, *phosphorus in agriculture*, and *recovery and recycling of phosphorus*) for understanding phosphorus sustainability.

The results revealed that the four big ideas that were incorporated into the definition of phosphorus sustainability are consistent with themes addressed in phosphorus sustainability literature (e.g., Barquet et al., 2019; Brownlie et al., 2022; Chowdhury et al., 2017; Zhang et al., 2022). These studies found the big ideas *circulating phosphorus*, *environmental pollution*

mitigation, and *healthy ecosystems* were also recommended by the expert panel. Research has shown that 80% of mined phosphate is lost to the environment (Childers et al., 2011), causing the eutrophication of surface waters (Jacobs et al., 2017; Stamm et al., 2022). Despite the popular definition of sustainable development, including the theme of *conservation for the future*, the participants in this study did not find it essential to include when defining phosphorus sustainability. It is suggested that this occurred because society will have sufficient access to phosphorus sustainability for the near future (Heckenmüller et al., 2014); therefore, emphasis and attention should currently be paid to the environmental and economic harm of phosphorus pollution (Edixhoven et al., 2014).

Discussion of the key concepts identified by the participants as important for phosphorus sustainability describes why educators should add them to curricula, lesson plans, and standards. The findings suggest lessons on eutrophication can connect to the lives of learners by identifying the personal impacts of the overuse of phosphorus on recreational activities, drinking water, and biodiversity students would experience because relevant lessons to students improve learning (Stuckey et al., 2013). Addressing the concepts of *food systems* and *phosphorus in agriculture* is important because food grown for human consumption is the primary non-point source of phosphorus pollution (Sabo et al., 2022). Reducing meat consumption and food waste will decrease the global demand for phosphorus (Metson et al., 2012) because livestock feed is one of the key factors driving phosphate demand (Helin & Weikard, 2019), and one-third of food produced is wasted (Sharma et al., 2020). Educating students on the behavioral choices of diet and food waste could promote these pro-environmental behaviors in students (Janmaimool & Khajohnmanee, 2019).

Chapter 3

The study presented in Chapter 3 was a qualitative interview study. Twenty phosphorus sustainability researchers from different disciplinary fields were interviewed using a semi-structured interview protocol. Interviews revealed concern among participants about the general lack of awareness of phosphorus sustainability challenges, impacts, and solutions from society. While it is important for the public to become aware of this topic, participants provided a positive perspective because the lack of awareness means phosphorus sustainability does not have the same public relations issues as climate change (McKie & Galloway, 2007). Having the public polarized on sustainability challenges can make education initiatives difficult (Kersting, 2023). This study recommends that educators consider the framing of their lessons carefully because message framing can significantly impact individual attitudes and behaviors (van de Velde et al., 2010). It is crucial that phosphorus sustainability education does not alienate stakeholder members and communities (e.g., farmers, agricultural industry).

Participants frequently mentioned the social, political, and economic factors associated with phosphorus sustainability in their responses; however, sustainability education has a history of being dominated through an environmental lens (Buchanan, 2012; Sinakou et al., 2019). The results support the recommendation that educators incorporate systems thinking into their teaching on phosphorus sustainability to assist with making connections between social, economic, and environmental factors, allowing them to approach phosphorus sustainability from a holistic view (Molderez & Ceulemans, 2018; Shaked & Schechter, 2017). Furthermore, the results suggested that phosphorus sustainability education is approached through an interdisciplinary perspective because students' sustainability competencies are improved when sustainability is presented through different disciplinary lenses (Walshe, 2017).

Participants recommended a variety of experiential learning opportunities, a derivative of constructivism (Bartle, 2015; Seaman, 2008), that could assist with teaching and learning phosphorus sustainability. Example activities included field trips to eutrophic surface waters or wastewater treatment plants, a variety of lab experiments, case studies, and discussions with stakeholder representatives, which have all been documented in studies to assist with learning sustainability competencies and content knowledge (Monroe et al., 2019; Noy et al., 2017; Wei et al., 2018). Incorporating creative opportunities and art, a form of experiential learning referred to as 'aesthetic learning' (Heras, 2022), into phosphorus sustainability education was also recommended as a technique to engage learners in thoughtful discussion and assist with learners engaging in phosphorus sustainability solutions. Lastly, personal relevance is a barrier to learners engaging in sustainability (Martin & Chen, 2016); therefore, it was suggested that educational lessons on phosphorus sustainability should connect to food, safe drinking water, and personal health.

Implications

The findings from this dissertation lay the groundwork for developing phosphorus sustainability education and draws attention to the lack of available resources and general knowledge of the topic in the education community. Education can be an effective tool to create positive change toward a more phosphorus-sustainable world because it can promote concern and pro-environmental actions in people (Corderoid et al., 2020; Jalil et al., 2023). Prior to this research, phosphorus sustainability was an ill-defined term lacking clarity and a variety of interpretations. An unambiguous definition is necessary for fruitful discourse, especially for terms that expand across several disciplinary fields (Wu & Hobbs, 2007). Educators will be able to incorporate the concise definition of phosphorus sustainability, which was developed using the

expertise of researchers, into their teaching. Using this definition can assist educators in avoiding challenges with instruction, lesson design, and student learning that have been previously reported due to elusive definitions of sustainability terms (Urdan & Luoma, 2020).

Phosphorus sustainability has the potential to become a crosscutting concept; however, because crosscutting concepts cross different disciplinary boundaries (National Research Council, 2012), it is important they are integrated into curricula in a coordinated manner (Fortus, 2015). Educators and education researchers can use the four key concepts presented in the Delphi study to develop curricular coherence.

The qualitative interview study has provided detailed suggestions on how phosphorus sustainability should be taught and learned, what subject matter to emphasize in lessons based on the audience (e.g., students vs. adult citizens), potential challenges educators and learners can expect, and strategies for overcoming these challenges. Prior to this study, little guidance was available to educators. However, educators now have multiple recommendations that can assist them with providing phosphorus sustainability education.

Limitations

When interpreting the results of this dissertation, it is important to recognize that these studies were descriptive. Suggestions and recommendations are based on participants' responses and prior sustainability research, and these perspectives have not been empirically tested or validated specifically for phosphorus sustainability. Additionally, time, costs, and panel size were limitations for the Delphi study. Including more survey rounds or participants may have resulted in additional big ideas to include when defining phosphorus sustainability or as critical concepts.

Another limitation of both studies was the years of experience working in phosphorus sustainability. A few participants for both studies had only a couple of years of experience working in the field. It is possible that people with fewer years of experience may have different perspectives on phosphorus sustainability than people with more years of experience. However, excluding people with only a few years of experience may have reduced the total sample size for both studies. A low number of participants would also be a limitation because it would limit the number of perspectives represented in the studies; therefore, it was important to include them. Despite some participants having only a few years of experience working with phosphorus sustainability, the participants had many years of experience working in other areas of sustainability; therefore, it was beneficial to include them in the studies.

Future Research and Actions

Both studies recommended that phosphorus sustainability education be personally relevant to the audience. This dissertation stated that food, safe drinking water, and personal health could be relevant topics to learners. Future research could evaluate whether these topics are personally relevant to people and determine if any other additional topics could be included. In addition, curriculum designers can take the recommendations suggested in these studies and develop educational materials (curricula, lessons, activities). Intervention studies can be conducted with the developed materials to measure the impacts the materials have on learners' pro-environmental behavior and general understanding and awareness of phosphorus sustainability.

This dissertation revealed four key concepts that could be important for understanding phosphorus sustainability, and further studies could be conducted to uncover other key concepts that could be important when learning about phosphorus sustainability. The next steps will

include developing coherent curricula for these key concepts and conducting validation studies to test the effectiveness of these curricula.

Lastly, professional development (PD) programs are needed to raise teachers' awareness of the importance of phosphorus sustainability. PD can assist teachers in learning effective tools and strategies for teaching about phosphorus sustainability and help them develop lessons that they can include in their classroom instruction. Along these lines, there needs to be a call to action among phosphorus sustainability researchers to collaborate with educators to assist with integrating phosphorus sustainability into current curricula. Teachers struggle to fit sustainability into their instruction due to content standards (Parry & Metzger, 2023); therefore, this collaborative effort between researchers and educators can assist educators with developing effective phosphorus-focused lessons that align with the content standards they are responsible for covering.

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APPENDICES

Appendix A

Delphi Study Codebook

Code Name	Definition	Exemplary Quotes
	Survey Question: In your own words, how should phosphorus sustainability be defined?	
Three Pillars of Sustainability	Description incorporates/considers one or more of the three fundamental components of sustainability (environment, social, economic) or any of its sub-components (e.g., equity, equality, justice, ethics, viable, bearable, etc.)	Phosphorus sustainability refers to a state where sufficient P is justly and affordably available to support food production.
Circulating Phosphorus in a Closed Loop	Description describes recycling, recovering, or reusing phosphorus to change the flow of phosphorus from unidirectional and lost from the system to a closed loop that can be reused over time.	Phosphorus sustainability is making phosphorus use and recovery into a cyclic process, recapturing and reusing phosphorus so its depletion rate (into unrecovered) phosphorus is minimized.
Conservation for Future	Description discusses the ability to have access to usable phosphorus sources to meet the phosphorus demands for future generations.	Phosphorus sustainability is satisfying the present phosphorus needs without sacrificing the phosphorus needs of the future.
Decrease Dependency on Mined Phosphate	Description describes reducing/decreasing humans' dependence on mined phosphate to meet society's phosphorus needs.	Phosphorus sustainability is having as little reliance on mined phosphorus as possible while meeting ecosystem health and food production goals.

Code Name	Definition	Exemplary Quotes
Environmental Pollution Mitigation	Description discusses minimizing, reducing, or preventing phosphorus pollution/runoff from entering the environment (e.g., waterways, aquatic environments) to mitigate the harmful effects excess phosphorus has on the environment.	Phosphorus sustainability mitigates ecological harm caused by phosphorus entering surface and ground waters from point and non-point sources.
Finite Resource	Description emphasizes phosphorus being a finite resource, which is when the consumption rate of a resource is faster than the rate at which the resource is formed or replenished.	Phosphorus is a finite resource, and its sustainability is important for the environment, economy, and future generations.
Healthy Ecosystems	Description incorporates the need to preserve the health of ecosystems by ensuring phosphorus management does not deplete its presence in the environment and is readily available.	Maintaining soil health and water quality at the same time.
Phosphorus Sources	Description states utilizing different sources of phosphorus (e.g., mines, soil, water, waste).	Phosphorus sustainability should mean the capacity and the exercise of human beings' choices that utilize science in all forms (mining, agriculture, wastewater treatment, economics, etc.) so that reserves of phosphorus in all forms (manure, compost, rock, etc.) are deployed to their highest and best use across the short, medium, and long term.
Scales of Phosphorus	Description describes phosphorus sustainability happening at different geographical scales (local, regional, national).	Preventing excess phosphorus from reaching the natural environment while maintaining self-sufficiency of phosphorus supply for agriculture and industry on local and global levels.
Sustaining and Improving Food Production	Description includes managing phosphorus and/or using technology that will allow the agricultural industry to continue functioning and producing adequate food to feed the world.	Phosphorus sustainability is the efficient management of phosphorus to support the production of food, fiber, and feed for a growing human population.

Code Name	Definition	Exemplary Quotes
Survey Question: In your own words, how should phosphorus sustainability be defined?		
Anthropogenic Impacts to Phosphorus Cycle	Description emphasizes the changes humans have created to the biogeochemical cycling of phosphorus and/or the impacts of the changes	Understanding anthropogenic disruptions to the phosphorus cycle and their consequences. This will highlight how humans have altered the natural biogeochemical cycles and the consequences of those disruptions, particularly in water quality.
Biological Properties	Description incorporates people understanding the basic biological science and processes revolving around phosphorus (e.g., DNA structures)	Biology basics: the use and importance of P in biological energy, DNA, structures, and all other systems.
Economic Factors of Phosphorus	Description discusses the impacts phosphorus management and use has on economies.	Market failure occurs when there are costs or benefits associated with an economic activity (such as agriculture) that are not reflected in the market price. This leads to an inefficient allocation of resources (such as phosphorus) because the harmful costs to society (water pollution) are not reflected in the cost of phosphorus, keeping the price too low and leading to less efficient use.
Environmental Factors of Phosphorus	Description highlights the need for people to understand the role of phosphorus in the environment or describes the negative impacts of too much or too little phosphorus on the environment.	Elevated phosphorus levels in waterbodies can cause significantly decrease water quality and damage aquatic ecosystems
Essential Element	Description addresses phosphorus being an essential element that all living things need and would die without.	The essential nature of P compounds for all organisms. It is not possible to substitute any other element for P in these compounds.

Code Name	Definition	Exemplary Quotes
Fertilizers	Description includes knowing and understanding fertilizers' role in phosphorus systems, how fertilizers are made, why we need fertilizers, and presenting data on fertilizer practices and usages.	Knowledge of the main types of phosphorus fertilizer, the chemistry of their production, and the resources and wastes produced.
Finite Resource	Description incorporates the finite nature of phosphate rock, the law of conservation and mass and energy, or knowledge of peak (production rate of mining phosphate reaches max capacity and after the rate decreases due to shrinking supply) vs end phosphorus (no mineable sources of phosphate).	Phosphorus is an atom; it cannot be created or destroyed; therefore, there is a finite amount of phosphate on earth.
Geological Properties	Description mentions knowing where phosphorus sources (e.g., phosphate rock) are naturally found worldwide and why.	P geology: Where P deposits are located and why, as well as why some parts of the world have very low P. Knowing basic P geology is important for understanding why mines are only located in a few parts of the world and why P is a finite resource.
Geopolitics	Description includes the need to understand the geopolitical challenges due to the geological distribution of phosphate rock sources and/or the importance of international relations with the global trading of phosphorus.	International relations is important because global markets influence the price of phosphate rock/synthetic fertilizers, which can create pressures, opportunities, and drive inequities in who uses what kind of P and when.
History of Phosphorus	Description discusses the importance of knowing the history of humans using phosphorus (e.g., discovery, past disputers, past P-related challenges/events).	Justice and equity issues around its history and use. (e.g., occupation of Western Sahara, colonial guano harvesting)
Life Cycle Analysis	Description emphasizes the need for people to be able to quantify the environmental impacts associated with phosphorus.	All should understand the meaning of an LCA, especially resource extraction and product disposal costs.

Code Name	Definition	Exemplary Quotes
Mass Balances	Description addresses the importance of knowing/understanding the mass flow of phosphorus and how it moves throughout natural and human-made systems and/or the inputs and outputs of the phosphorus system.	Nutrient budgets and mass balances at multiple scales (watershed to global): Where does phosphorus come from, who uses it, where are the major losses, and how do these balances vary globally?
Metrics, Units, & Data	Description mentions needing to understand how P is measured, how different stakeholders use different metrics to measure phosphorus, and what metrics count as sustainable and unsustainable usage.	Metrics and Units: everyone measures P differently (mass concentration - mgP/L or mgP/kg soil or mgP/kg food, fluxes (kgP/year), etc.).
Mining	Description discusses the importance of understanding the process of mining phosphate rock and the role/impacts mining has on the phosphorus system.	Mechanics of mining phosphate rock deposits and their chemical conversion to soluble forms in fertilizer manufacturing.
Mitigating Phosphorus Loss	Description touches on reducing the amount of phosphorus lost from the system to the environment via runoff, waste, etc.	Optimal use to benefit crop production while minimizing the risk of phosphorus loss to the environment is essential for the long-term sustainability of agriculture
Plant Usage	Description addresses how plants utilize phosphorus.	Understanding plant requirements for phosphorus and how they access it in soils.
Phosphorus Chemistry	Description mentions the importance of knowing the different structures and forms of phosphorus (e.g., inorganic phosphorus vs organic phosphorus)	Understanding the chemistry of phosphorous, particularly as it relates to solubilization and mobilization in the soil, is important because this determines plant availability of this nutrient and the risk of loss due to runoff and leaching.
Phosphorus Cycle	Description addresses the importance of understanding how phosphorus cycles in an ecosystem or refers to the nutrient/biogeochemical cycle of phosphorus (does not address anthropogenic impacts).	P cycle: How P moves through the landscape, placing particular emphasis on the fact that it binds to soils, occurs in dissolved forms in water, and does not have a gaseous phase (in contrast to nitrogen).

Code Name	Definition	Exemplary Quotes
Phosphorus in Agriculture	Description emphasizes phosphorus's role in food webs, the ability to feed people and living things, and/or the impact (positive or negative) of using it in agriculture systems.	Understanding the relationship between phosphorus, food systems, and food security. The availability of phosphorus to farmers is essential for food security.
Physical Properties	Description includes understanding the basic physical properties and/or processes of phosphorus	Physics: Problems and solutions always need to be underpinned by physical constraints and functioning.
Recovery and Recycling of Phosphorus	Description emphasizes the need for recovering and recycling phosphorus (e.g., circular flow/closed loop vs unidirectional flow)	Understanding opportunities to recycle phosphorus-rich organic materials. A transition to sustainable phosphorus use relies on the efficient recycling of phosphorus rich organic materials
Regulations and Policies	Description mentions current, future, and past (or lack thereof) regulations and/or policies for managing phosphorus	Environmental governance: what are possible laws, regulations, industry standards, and community norms that control what stakeholders do; can they be altered to change behavior or incentives?
Social Factors of Phosphorus	Description describes the need for people to understand the ethical, just, and equitable components of phosphorus or the human health impacts of having too much or too little phosphorus.	No community should be able to dominate the use of a resource to the detriment of another community simply because one community is more powerful or affluent than another.
Soil Sciences	Description includes the role phosphorus plays in soils, how it behaves in soil, and its ability to build up in soils due to the continuous application of fertilizers.	Phosphorus-soil interactions: students should be taught P sorption phenomena in soil organic matter and various primary and secondary minerals; the lesson should describe pH effects.

Code Name	Definition	Exemplary Quotes
Solutions	Description addresses solutions (e.g., technology) that would promote a more sustainable use of phosphorus.	technology that fits the needs of the users and is effective and affordable. The challenges in the global South are very different than the global North - there is not going to be a one one size fits all tech.
Sources of Phosphorus	Descriptions describe the importance of knowing the different sources of phosphorus.	The diversity of phosphorus sources and related processes should be taken into account in sustainability assessments.
Systems Thinking	Description addresses the need for analyzing phosphorus from a holistic approach that observes all the interrelated parts of the phosphorus system and how it functions over time within the context of other systems.	The capacity to make connections among system features that might be different in nature, identify feedback loops, and generally acknowledge complexity. Many decisions about P affect other issues, and other issues affect P. Without a systems understanding, interventions are likely to be ineffective.
Transdisciplinary	Description mentions the need to understand, combine, and/or utilize different disciplinary knowledge.	Transdisciplinary: how to combine different disciplinary knowledge and 'other' forms of knowledge (e.g., stakeholders).
Waste Systems	Description includes an understanding of current phosphorus waste management techniques (e.g., anaerobic digesting process, biological nutrient removal, and struvite crystallization).	Knowledge of the anaerobic digestion process and how it affects solubilization of P from human and animal wastes.
Wicked Problems	Description addresses phosphorus sustainability as a difficult/complex challenge due to a lot of interconnecting favors from other sustainable development challenges (e.g., climate change).	Wicked Problems: important because P sustainability is a highly complex, interdependent problem where our efforts can have unintended consequences that might fall into our blind spots.

Appendix B

Round 2 Delphi Survey Items

Part 1: Defining Phosphorus Sustainability

For the following "big ideas," please rate the level of importance (not important to extremely important) of each idea in relation to the following question: *"How important is it to include this idea when defining phosphorus sustainability?"*

Q1. **Big Idea:** ***Three Pillars of Sustainability***
Summary: When defining phosphorus sustainability, it should recognize phosphorus' role, impacts, and/or usages in each of the three fundamental components of sustainability (economic, social, and environmental) and its sub-components (e.g., equity/equality, justice, ethics), etc.)
Exemplary Supporting Statements:
1) The balanced and responsible use of phosphorus among various users and sectors, such as agriculture and industry.
2) The use of phosphorus that does not deplete mineable reserves and fosters environmental stewardship while enabling an equitable and stable global food system.
3) Involves aspects of environmental integrity, human rights (especially the right to food), poverty and inequality, resilience, and food security.
4) The utilization of phosphorus resources to enhance human well-being and the functioning of ecosystems.
5) Supports positive economic outcomes for communities and industries that utilize and provide phosphorus.

Q2. **Big Idea:** ***Circulating Phosphorus in a Closed Loop***
Summary: When defining phosphorus sustainability, it should address the need to change the current unidirectional flow of phosphorus to a closed loop through recycling, recapturing, or reusing phosphorus from a variety of sources (e.g., agricultural manure, human sewage/waste streams, the environment: lakes and soil)
Exemplary Supporting Statements:
1) The ability to generate circular flows of phosphorus that include production, use, and recovery.
2) The reuse of phosphorus-containing materials.
3) The recapturing and reusing of phosphorous so its depletion rate (into unrecoverable phosphorous) is minimized.
4) The requirement to develop pathways for efficient and effective phosphorus recovery and reuse from municipal and industrial waste streams.

Q3. **Big Idea:** ***Conservation for the Future***
Summary: When defining phosphorus sustainability, it should emphasize the ability to meet society's phosphorus needs in today's world without compromising the ability of future generations to meet their phosphorus needs.

Exemplary Supporting Statements:
1) The use and management of phosphorus that meets the needs of the present without compromising the needs/well-being of future generations.
2) Its sustainability is important for future generations.
3) Acknowledges and balances the use of current and future users.

Q4. **Big Idea:** ***Decrease Dependency on Mined Phosphate***
Summary: When defining phosphorus sustainability, it should mention reducing/decreasing the amount of mined phosphate humans extract from phosphate reserves to meet society's phosphorus needs.
Exemplary Supporting Statements:
1) The reduction or elimination in mining of phosphate rock.
2) Have as little reliance on mined phosphorus as possible.
3) There is no (or very little) additional need for the mining of phosphorus for use in agricultural production.
4) Reduction of reliance of imported (mined) phosphorus.
5) Avoiding the use of newly mined products where possible.

Q5. **Big Idea:** ***Environmental Pollution Mitigation***
Summary: When defining phosphorus sustainability, it incorporates preventing, reducing, and/or minimizing phosphorus pollution/runoff/excess phosphorus from entering the environment (e.g., waterways, aquatic environments, soil) and polluting/harming it.
Exemplary Supporting Statements:
1) Minimizing phosphorus transfer from land to waterways.
2) Involves minimizing its loss in waterways or fixation in soil.
3) Involves minimizing the environmental impacts.
4) Responsible management of phosphorus without degrading our soil and water systems.
5) The efficient use and extraction of global phosphorus resources in a way that limits environmental impacts across the phosphorus life cycle.

Q6. **Big Idea:** ***Finite Resource***
Summary: When defining phosphorus sustainability, it should state how phosphorus is a finite resource. (*finite resource is defined as a resource that has a consumption rate that is faster than the rate at which the resource is replenished)
Exemplary Supporting Statements:
1) Phosphorus is a finite resource.
2) Apply only the amount required for optimal crop productivity so that this finite resource should be there for generations.

Q7. **Big Idea:** ***Healthy Ecosystems***
Summary: When defining phosphorus sustainability, it addresses the need to create healthy ecosystems and/or maintain the health of ecosystems when using phosphorus.
Exemplary Supporting Statements:

1) Meets societal needs for phosphorus while protecting the long-term health and functionality of the ecosystem.
2) Use of phosphorus that fosters environmental stewardship.
3) Maintains soil health and water quality at the same time.
4) The ability to use phosphorus in an environmentally-friendly way

Q8. **Big Idea:** ***Phosphorus Sources***
Summary: When defining phosphorus sustainability, it should emphasize using different sources of phosphorus (e.g., manure, compost, rock) that are available or efficiently using phosphorus resources.
Exemplary Supporting Statements:
1) The efficient use and extraction of global phosphorus resources.
2) All the phosphorus used is obtained from sources such as composts, manures, and sewage/waste streams.
3) Does not deplete mineable reserves.
4) Reserves of phosphorus in all forms (manure, compost, rock, etc.) are deployed to their highest and best use.

Q9. **Big Idea:** ***Scales of Phosphorus***
Summary: When defining phosphorus sustainability, it should address the need to address the topic at different geographical scales (local, regional, national).
Exemplary Supporting Statements:
1) Maintaining self-sufficiency of phosphorus supply for agriculture and industry on local and global levels.
2) Sustainability of a particular nation, region, socioeconomic system, or global human society.
3) The ability to generate circular flows of phosphorus at local (e.g., a farm), regional (e.g., watershed), and national (e.g., country) scales.

Q10. **Big Idea:** ***Sustaining and Improving Food Production***
Summary: When defining phosphorus sustainability, it needs to emphasize developing management practices and or technology that will allow the agricultural industry to continue to function/produce enough food to feed the world.
Exemplary Supporting Statements:
1) Efficiently managing the use of phosphorus to support the production of food, fiber, and feed for a growing human population.
2) Involve stakeholders with new food production approaches where phosphorus use may be more sustainable.
3) Have as little reliance on mined phosphorus as possible while meeting food production goals.
4) The capacity to access sufficient P to feed people equitably.
5) Maximizes phosphorus use in the production of proteins and carbohydrates for food production.

Part 2: Key Concepts for Understanding Phosphorus Sustainability

For the following "big ideas," please rate the level of importance (not important to extremely important) of each idea in relation to the following question: *"How important is teaching this idea in order to understand phosphorus sustainability?"*

Q11. **Big Idea:** ***Economic Factors of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to know the influences and impacts phosphorus management and use have on economies.
Exemplary Supporting Statements:
1) A person should know the economics associated with the sourcing, using, and environmental harm of phosphorus.
2) Understanding techno-economic impacts of mining P, techno-economic impacts over its lifecycle (from mining to use to disposal, run-off), and techno-economic challenges of its mismanagement and run-off (e.g., technologies and economic considerations of eutrophication, harmful algal blooms).
3) Market failure is important to understand because it occurs when there are costs or benefits associated with an economic activity (such as agriculture) that are not reflected in the market price. This leads to an inefficient allocation of resources (such as phosphorus) because the harmful costs to society (water pollution) are not reflected in the cost of phosphorus, keeping the price too low and leading to less efficient use.

Q12. **Big Idea:** ***Environmental Impacts of Phosphorus***
Summary: To understand phosphorus sustainability, people need to understand the role phosphorus has in the environment/ecosystems. People should know the impacts of having too much or too little phosphorus has on the environment (e.g., eutrophication, water quality issues)
Exemplary Supporting Statements:
1) An important concept to be aware of is nutrient limitations in aquatic systems and the consequences of nutrient imbalances and excess loading of phosphate.
2) Knowledge of the environmental effects of P, especially eutrophication, and an understanding of the different roles of P and N in freshwater versus marine environments.
3) Knowledge of eutrophication and how water bodies are degrading by amplified inputs of nutrients.
4) Awareness of ecosystem ecology. One should understand biotic and abiotic processes that affect the flow of P in and between ecosystems. Aquatic systems are particularly important given how eutrophication affects their functioning.

Q13. **Big Idea:** ***Social Factors of Phosphorus***
Summary: To understand phosphorus sustainability, people need to understand the social implications and considerations (ethical, justice, equity, etc.) of phosphorus. People should know the impacts of phosphorus on society and the ethical considerations or lack thereof.
Exemplary Supporting Statements:
1) It is important to know societies need fair allocation and use of resources. No community should be able to dominate the use of a resource to the detriment of another community simply because one community is more powerful or affluent than another.

2) One should know the societal and ethical impacts of P management and use. This includes understanding the societal/ethical impacts of mining P, the societal/ethical impacts over its lifecycle (e.g., from mining to use to disposal, run-off), and the societal/ethical challenges of its mismanagement and run-off (e.g., disproportional impacts of eutrophication, harmful algal blooms across different communities).

Q14. **Big Idea:** ***Human Health Impacts***
Summary: To understand phosphorus sustainability, it is important to be insightful on the impacts having too much or too little phosphorus has on human health.
Exemplary Supporting Statements:
1) A person should be aware of the role of P compounds in public health. For example, phosphate is added to drinking water in most major cities globally to prevent lead leaching in drinking water.
2) Knowing the human health impacts of P management and use is an important concept. A person should understand the human health impacts of mining P and the health challenges of its mismanagement and run-off (e.g., toxic effects of harmful algal blooms).

Q15. **Big Idea:** ***Anthropogenic Impacts to Phosphorus Cycle***
Summary: To understand phosphorus sustainability, it is essential to be aware of humanity's role in disrupting/changing the biogeochemical cycle of phosphorus. Individuals should know the impacts humans have had on this naturally occurring cycle.
Exemplary Supporting Statements:
1) A basic understanding of how humans have impacted the phosphorus cycle is needed. For example, how humans' use of phosphorus has impacted agricultural production, impacts of human fertilizer application, global food markets, etc.
2) A key concept is understanding anthropogenic disruptions to the phosphorus cycle and their consequences. This will highlight how humans have altered the natural biogeochemical cycles and the consequences of those disruptions, particularly in water quality.
3) To understand impacts and solutions an individual should know the flows of phosphorus through the anthropogenic phosphorus cycle to understand impacts and solutions.

Q16. **Big Idea:** ***Geopolitics***
Summary: To understand phosphorus sustainability, it is important to recognize how phosphorus management is a geopolitical challenge because phosphorus is located only in certain parts of the world, making its distribution and access volatile. It is important to understand international relations regarding phosphorus due to the geographical restraints of phosphorous sources and to understand the need for responsible phosphorus management on a global scale.
Exemplary Supporting Statements:
1) A critical concept for understanding phosphorus sustainability is international relations. This is important because global markets influence the price of phosphate rock/synthetic fertilizers, which can create pressures and opportunities and drive inequities in who uses what kind of P and when.
2) A person should be aware of the effects of cartels, market power, and international commodity markets because natural finite resources that are only mined in a few locations can be subject to oligopoly (market power). This allows producers to manipulate the price by changing how much

is produced. The more the world depends on mined finite phosphorus, the more market power those few producers will enjoy.
3) The scarcity of phosphate rocks around the world has led to interesting geopolitical situations.

Q17. **Big Idea:** ***History of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to be aware of the history of humans using P. One should know how humans discovered phosphorus and its importance, past disputes that have occurred over phosphorus, and past phosphorus-related challenges and events.
Exemplary Supporting Statements:
1) A concept people need is knowledge of the history of P. One should know about its discovery, extraction, measurement, and subsequent applications so that anyone working with or around P issues has a common baseline knowledge of the substance.
2) A person should know of past examples of harmful impacts of phosphorus- for example, guano harvesting and occupation of Western Sahara.

Q18. **Big Idea:** ***Mass Balances ("P Flow Diagram")***
Summary: To understand phosphorus sustainability, it is essential to understand its input, output, and distribution throughout different systems. Mass balances are necessary for demonstrating the conservation of mass in phosphorous systems.
Exemplary Supporting Statements:
1) An important concept is phosphorus sources and flows because a person should understand where this finite resource comes from and where it goes
2) A person should understand nutrient budgets and mass balances at multiple scales (e.g., watershed to global) because it is important to know where phosphorus comes from, who is using it, where are the major losses, and how these balances vary globally.
3) P flow diagrams are important because phosphorus is present in an array of otherwise seemingly disparate processes across both the natural world and human-made infrastructure systems.
4) The skill of completing a mass balance is essential. Tracking the inputs of phosphorus, the reactions, and outputs of any system (e.g., farm, lake, wastewater facility) can help one determine if phosphorus circularity is achieved or not. Mass balances involve defining the boundaries of a system, quantifying all of the inputs and outputs, and identifying any reactions that can increase or decrease the species of interest (in this case, the species would be phosphorus).

Q19. **Big Idea:** ***Life Cycle Analysis***
Summary: To understand phosphorus sustainability, individuals need to quantify the environmental impacts associated with phosphorus products over the products' entire lifespan.
Exemplary Supporting Statements:
1) All should understand the meaning of a life cycle analysis, especially resource extraction and product disposal costs.
2) Life cycle assessments are important because a person should consider phosphorus processes from cradle to grave. We need to look at the whole supply chain/life cycle of P to assess its sustainability

Q20. **Big Idea:** ***Metrics, Units, and Data***
Summary: To understand phosphorus sustainability, it is important to know how P is measured and that different stakeholders use different systems for measuring phosphorus.
Exemplary Supporting Statements:
1) Everyone measures P differently (mass concentration - mgP/L or mgP/kg soil or mgP/kg food, fluxes (kgP/year), etc.)
2) To understand and integrate the large amounts of existing global data, it is important to understand data science.

Q21. **Big Idea:** ***Phosphorus Cycle***
Summary: To understand phosphorus sustainability, a person must understand how phosphorus cycles in ecosystems. A person should understand the nutrient/biogeochemical cycle of phosphorus and the science of how phosphorus naturally circulates and moves through the world.
Exemplary Supporting Statements:
1) The concept of P cycling and the major sources and sinks of P need to be better taught. Understanding the processes of weathering, erosion, transport, deposition, biological uptake, and recycling is crucial for knowing where steps can be taken to improve sustainability. Unlike the C and N cycles, the P cycle gets much less attention in both research and education. Enhancing P cycling education is important for increasing understanding of the fate and transport of P in the environment because it provides a framework for understanding the impacts of P management decisions.
2) The P cycle should be clearly defined and described to understand phosphorus sustainability.

Q22. **Big Idea:** ***Biological Properties of Phosphorus***
Summary: To understand phosphorus sustainability, a person needs to know the basic biological science principles around phosphorus. For example, how living things use phosphorus (e.g, DNA structures), and the inefficiencies of all biological systems (e.g., waste).
Exemplary Supporting Statements:
1) Teaching the biological science of phosphorus is important because understanding the requirements and use of P in the biosphere is critical to understanding global dynamics and requirements.
2) It is important to know the role of biology in phosphorus availability.
3) Knowing the biology basics of phosphorus is important. A person should know the use and importance of P in biological energy, DNA, structures, and all other systems.

Q23. **Big Idea:** ***Essential Element***
Summary: To understand phosphorus sustainability, it is important to know that all living things need phosphorus and that it is a nutrient living things have to get from external sources. Life can not continue without phosphorus, and no substitute/alternative forms exist.
Exemplary Supporting Statements:
1) A person should understand the importance of P as an essential nutrient for plants and animals.
2) It is important to know the essential nature of P compounds for all organisms, from ATP for energy to phospholipids and lipoteichoic acids in cell walls and RNA and DNA. It is not possible to substitute any other element for P in these compounds.

3) Understanding phosphorus as a nutrient is essential because phosphorus is one of the building blocks of life. It is needed for all living things to grow (for better, as in crops, and worse, as in cyanobacteria).

Q24. **Big Idea:** ***Finite Resource***
Summary: To understand phosphorus sustainability, it is important to know the law of conservation of mass and energy (mass is neither created nor destroyed in chemical reactions), which is why there is a limited amount of phosphorus available in the world.
Exemplary Supporting Statements:
1) Phosphorus is a chemical element/atom; it cannot be created or destroyed. Therefore, there is a finite amount of phosphorus on earth.
2) Phosphorus is not common. Phosphate rock, from which much of current phosphorus fertilizer is used, is found only in certain parts of the world.
3) It is important to understand the finite nature of phosphorus in order to avoid its depletion and address potential conflicts over its appropriation.

Q25. **Big Idea:** ***Geological Properties of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to know where phosphorus sources (e.g., phosphate rock) are naturally found in the world and the geological process that led to the creation of these phosphate rock resources.
Exemplary Supporting Statements:
1) It is important to understand the geology of phosphorus (e.g., Where P deposits are located and why some parts of the world have very low P).
2) Knowing basic P geology is important for understanding why mines are only located in a few parts of the world and why P is a finite resource. Understanding that some areas naturally have very low P also provides the background information needed to understand how P can become a pollutant.

Q26. **Big Idea:** ***Chemical*** **Properties** ***and Structures of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to understand the different structures and forms of phosphorus (e.g., proteins, inorganic P vs organic P, dissolves vs particulate, precipitated vs absorbed, orthophosphates vs organophosphates).
Exemplary Supporting Statements:
1) A person should know the forms of phosphorus and its interactions with other elements and materials, including bonds, adsorption, and speciation.
2) Understanding the chemistry of phosphorous, particularly regarding solubilization and mobilization in the soil, is important because this determines plant availability of this nutrient and the risk of loss due to runoff and leaching. Educating individuals about the importance of managing phosphorus inputs and outputs in agricultural and urban systems would be beneficial across a wide range of industries, from manufacturing and agriculture to wastewater treatment and freshwater management. This would enable the development of strategies for reducing phosphorus runoff, optimizing fertilizer use, and implementing wastewater treatment technologies.
3) It is important to understand the different forms of phosphorus (e.g., orthophosphates vs. organophosphates) because plants uptake ortho-P, not organo-P.

4) Understanding how P binds to materials and can be transformed is important.

Q27. **Big Idea: Physical *Properties of Phosphorus***
Summary: To understand phosphorus sustainability, one should know about the physical properties and processes of phosphorus.
Exemplary Supporting Statements:
1) Knowing the physical science of phosphorus is important because problems and solutions always need to be underpinned by physical constraints and functioning.
2) The physical processes affect how P moves in soil systems, affects crop yields and losses to waterways.

Q28. **Big Idea: *Soil Sciences and Legacy Phosphorus***
Summary: Knowing how phosphorus behaves in soil and the importance of soil health is important to understand phosphorus sustainability. One should be aware that phosphorus can build up in soils (known as legacy P) due to the continuous application of fertilizers beyond what plants actively need.
Exemplary Supporting Statements:
1) An important concept is understanding that much of the P in the soil is unavailable to plants and that applied P can quickly be tied up in the soil.
2) It is important to understand how phosphorus behaves in soils. People should know what happens when fertilizer is applied to soil in the short and long term, how 'legacy' phosphorus can be utilized, and what the role of organic phosphorus in soils is.

Q29. **Big Idea: *Sustainable Solutions***
Summary: To understand phosphorus sustainability, it is important to understand the solutions (e.g., management practices, technology, consumer changes, etc.) that will allow for the more sustainable use of phosphorus. It is important to know that sustainable solutions are not a one-size-fits-all model and that different areas of the system might need different solutions from other areas.
Exemplary Supporting Statements:
1) It will be especially important not to overemphasize technical solutions to problems that can be addressed by implementing already available policies and practices (i.e. technology as a political suppression tactic).
2) The importance of engineering solutions to nutrient imbalances should be recognized.
3) It is important to know about appropriate technology. Technology that fits the needs of the users and is effective and affordable. The challenges in the global South are very different than those in the global North - there will not be a one-size-fits-all tech.
4) Understanding the pathways and obstacles to implementing solutions.
5) Understanding proposed solutions to P sustainability problems.

Q30. **Big Idea: *Regulations and Policies***
Summary: To understand phosphorus sustainability, it is important to have knowledge and awareness of the role of past, current, and/or potential future regulations and policies for managing phosphorus.

Exemplary Supporting Statements:
1) A key concept for understanding phosphorus sustainability is knowledge of regulations and policies related to P management and use.
2) Knowledge of payment for ecosystem services.
3) An important concept is Environmental governance. It is important to understand the possible laws, regulations, industry standards, and community norms that control what stakeholders do and the challenges and reality of changing stakeholder behavior and offering incentives.
4) It is important to understand the role of incentives and how they drive the behavior of P users. Incentives often encourage unsustainable P use. Incentives can also be used to discourage it (for example, via fertilizer taxes or bans on fall fertilizer applications).

Q31. **Big Idea:** ***Recovery and Recycling of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to understand the role that recovering and recycling phosphorus will have in the sustainable use of phosphorus. The current use of phosphorus flows is uni-directional; recycling and recovering phosphorus will assist with closing the loop for phosphorus flow.
Exemplary Supporting Statements:
1) An important concept would be ways that P can be recycled and reused (e.g., composting to removal from wastewater treatment).
2) Understanding opportunities for recovering phosphorus from residue streams is important. Many technologies exist to recover phosphorus from residue streams, which can then be used to create new products to facilitate phosphorus recycling (e.g., recycled fertilizers)
3) It is important to know strategies for closing the loop of the P cycle on-farm and preventing losses to the environment.
4) Recycling phosphorus from wastewater and other waste streams is important for understanding phosphorus sustainability.

Q32. **Big Idea:** ***Sources of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to know the different sources of phosphorus (e.g., waste, soil, water systems, phosphate rocks/mines, etc.). Additionally, it is important to recognize the difference between available phosphorus resources and phosphorus reserves.
Exemplary Supporting Statements:
1) Recognition that there are other P sources than fertilizer and that their contribution to a sustainable agricultural sector needs to be taken into account. Manure use can offset the need for purchased fertilizers, which is important.
2) The diversity of phosphorus sources and related processes should be taken into account.
3) An understanding of phosphorus reserves, resources, and uses. Most phosphorus inputs used by society come from finite reserves of phosphate rock located in only a few countries.

Q33. **Big Idea:** ***Systems Thinking***
Summary: To understand phosphorus sustainability, it is important to have the skill to analyze phosphorus from a holistic approach that emphasizes all the interrelated parts of the phosphorus system and how it functions over time within the context of other systems (e.g., climate change,

geopolitical/social/economic factors); making sense of phosphorus system in terms of wholes and relationships rather than splitting down into its parts.

Exemplary Supporting Statements:

1) Systems thinking, which is the capacity to make connections among system features that might be different in nature, identify feedback loops, and generally acknowledge complexity, is a key skill for understanding phosphorus sustainability. Many decisions about P affect other issues, and other issues affect P. Without a systems understanding interventions are likely to be ineffective.

2) An important skill is a synthesis view of P as part of a complex social-ecological-technological system and explores options, opportunities, trade-offs, and obstacles around a fundamental transformation of the P system toward sustainability. This is an advanced look at the potential for P transformation to allow people to interrogate and propose solutions at a system level.

Q34. **Big Idea:** ***Transdisciplinary Thinking***

Summary: An important skill for understanding phosphorus sustainability is transdisciplinary thinking. It is important to understand, combine, and utilize different disciplinary knowledges that play a role in phosphorus sustainability.

Exemplary Supporting Statements:

1) Transdisciplinarity is a key skill because it is important to know how to combine different disciplinary knowledge and 'other' forms of knowledge.

Q35. **Big Idea:** ***Wicked Problems***

Summary: To understand phosphorus sustainability, it is important to know that achieving phosphorus sustainability is challenging because there are alot of connecting factors from other sustainable development challenges (e.g., climate change). Wicked problems, like phosphorus sustainability, have multiple interconnected challenges and issues and many potential solutions, each with pros and cons.

Exemplary Supporting Statement:

1) The concept of wicked problems is essential because P sustainability is a highly complex, interdependent problem where our efforts can have unintended consequences that might fall into our blind spots.

Q36. **Big Idea:** ***Waste Systems***

Summary: To understand phosphorus sustainability, it is important to understand the role and impact of waste systems in managing phosphorus.

Exemplary Supporting Statements:

1) A key concept is knowledge of the anaerobic digestion process and how it affects the solubilization of P from human and animal wastes.

2) Understanding Biological Nutrient Removal (BNR) in sewage treatment, such as the Bardenpho process.

3) Knowledge of crystallization technologies for removing P from anaerobic digester filtrate and other wastewaters, especially struvite crystallization.

4) An important concept is sanitation/organic waste management engineering. Understand system options and functioning and how different contexts may require different options to treat

excreta, food waste, and yard waste not only for P but also to be socially, economically, and environmentally desirable.
5) We need people to design new wastewater and organic matter recycling technologies. Some waste products high in P are inevitable and need to be managed and recycled; thus, organic waste management is key to P's sustainability.

Q37. **Big Idea:** ***Fertilizers***
Summary: To understand phosphorus sustainability, it is important to know the role fertilizers play in phosphorus systems, how fertilizers are made, why we need fertilizers, and current fertilizer practices and usage.
Exemplary Supporting Statements:
1) A key concept is phosphorus fertilizers. A person should know the pros and cons of organic and inorganic sources of P, controlled-release, soluble granular, and liquid-applied P fertilizers and their individual implications on crop productivity, P use efficiency, and runoff/leaching potential.
2) A key concept is understanding the central role of fertilizer in maintaining high yields.

Q38. **Big Idea:** ***Mining***
Summary: To understand phosphorus sustainability, it is important to know the role mining plays in phosphorus systems and the mechanics of mining phosphate rock.
Exemplary Supporting Statements:
1) A key concept is the mechanics of mining phosphate rock deposits and their chemical conversion to soluble forms in fertilizer manufacturing.
2) It is important to know that phosphorus fertilizer is mined.
3) Phosphate mining and global P reserves are important concepts.

Q39. **Big Idea:** ***Phosphorus in Agriculture***
Summary: To understand phosphorus sustainability, it is important to know the role phosphorus plays in agriculture systems (e.g., meeting the nutritional needs of livestock and crops) and the impacts agriculture has on the phosphorus system.
Exemplary Supporting Statements:
1) Understanding the opportunities for better phosphorus use in agriculture. There are many opportunities to improve phosphorus use efficiency in agriculture, underpinned by the concept of circular economies.
2) The role of P in animal husbandry, including knowledge of the fate of P in animal husbandry.
3) A key concept is the agricultural science regarding phosphorus. For example, the efficiency of its uptake in crops and harvest and an understanding of leaching and erosion losses of P from agricultural activity.
4) People should know how our current agricultural system works (e.g., moving P through the environment, contribution to excess P and its impacts).
5) Knowing the need to replenish nutrients removed by agricultural harvests is important.
6) An important concept is reducing phosphorus losses from agriculture. Loss of phosphorus from soil systems requires knowledge and skills around P transport and connection of crop fields to waterways through transport pathways

Q40. **Big Idea:** ***Food Systems***
Summary: To understand phosphorus sustainability, it is important to be aware of the role phosphorus plays in food systems and the ability to produce food and feed people.
Exemplary Supporting Statements:
1) An understanding of the relationship between phosphorus, food systems, and food security. The availability of phosphorus to farmers is essential for food security.
2) A key concept to know is P's influence on food security.
3) Knowing the role P plays in the human diet is important.
4) A key concept is the role phosphorus plays in food security.

Q41. **Big Idea:** ***Utilization of Phosphorus in Plants***
Summary: To understand phosphorus sustainability, knowing how plants utilize phosphorus is important.
Exemplary Supporting Statements:
1) Importance of improving P uptake and utilization by plants.
2) It is important to know the factors influencing the availability of the phosphorus forms found in soil to plants.
3) An important concept to understand is plant P uptake.

Appendix C

Round 3 Delphi Survey Items

Part 1: Defining Phosphorus Sustainability

For the following "big ideas," please rate the level of importance (not important to extremely important) of each idea in relation to the following question: *"How important is it to include this idea when defining phosphorus sustainability?"*

Q1. **Big Idea:** ***Three Pillars of Sustainability***
Summary: Any definition of phosphorus sustainability should recognize phosphorus' role, impacts, and/or usages in each of the three fundamental components of sustainability (economic, social, and environmental) and its sub-components (e.g., equity/equality, justice, ethics), etc.).
Exemplary Supporting Statements:
1) The balanced and responsible use of phosphorus among various users and sectors, such as agriculture and industry.
2) Fosters environmental stewardship while enabling equitable access to phosphate products (e.g., fertilizers).
3) The use of phosphorus resources to enhance human well-being while protecting ecosystems.
4) Supports positive economic outcomes for communities and industries.

Q2. **Big Idea:** ***Circulating Phosphorus***
Summary: When defining phosphorus sustainability, it should enhance the concept of recycling, recapturing, or reusing phosphorus from a variety of sources (e.g., agricultural manure, human sewage/waste streams, the environment: lakes and soil).
Exemplary Supporting Statements:
1) The ability to generate circular flows of phosphorus that include production, use, and recovery.
2) The recycling of phosphorus embedded within materials.
3) The capture and appropriate reuse of phosphorus so its depletion rate (into difficult-to-recover phosphorus) is minimized.
4) The requirement to develop pathways for efficient and effective phosphorus recovery and reuse from municipal and industrial waste streams.

Q3. **Big Idea:** ***Conservation for the Future***
Summary: When defining phosphorus sustainability, it should emphasize the ability to meet society's phosphorus needs in today's world without compromising the ability of future generations to meet their phosphorus needs.
Exemplary Supporting Statements:
1) The use and management of phosphorus that meets the needs of the present without compromising the needs/well-being of future generations.
2) The ability of future generations to innovate new technologies and practices for using and managing phosphorus.

3) Acknowledges and balances the use of current and future users.

Q4. **Big Idea:** ***Decrease Dependency on Mined Phosphate***
Summary: When defining phosphorus sustainability, it should mention reducing the amount of mined phosphate that humans extract from phosphate reserves to meet society's phosphorus needs.
Exemplary Supporting Statements:
1) Reduction of reliance on mined phosphate rock by recycling phosphorus already extracted from mines.
2) Have as little reliance on mined phosphate as possible in order to reduce monopolies, geopolitical insecurity, and world prices that make a reliance on imported mined phosphate a vulnerability for most regional/national food systems.

Q5. **Big Idea:** ***Environmental Pollution Mitigation***
Summary: When defining phosphorus sustainability, it should include preventing or reducing excess amounts of phosphorus from entering the environment (e.g., waterways, aquatic environments, soil) and polluting the environment above homeostatic phosphorus levels.
Exemplary Supporting Statements:
1) Minimizing excess phosphorus transfer from land to waterways.
2) Responsible management of phosphorus without degrading our soil and water systems.
3) The efficient use and extraction of global phosphorus reserves in a way that limits environmental impacts across the phosphorus life cycle.

Q6. **Big Idea:** ***Healthy Ecosystems***
Summary: When defining phosphorus sustainability, it should address the need to maintain or create healthy ecosystems when using phosphorus.
Exemplary Supporting Statements:
1) Meets societal needs for phosphorus while protecting the long-term health and functionality of the ecosystem.
2) Use of phosphorus that reflects environmental stewardship.
3) Using phosphorus while maintaining soil health and water quality at the same time.
4) The ability to use phosphorus in an environmentally friendly way.

Q7. **Big Idea:** ***Phosphorus Sources***
Summary: When defining phosphorus sustainability, it should emphasize the variety of phosphorus sources (some being easier to extract or utilize than others) and the need to use multiple sources.
Exemplary Supporting Statements:
1) The efficient use and extraction of global phosphorus resources.
2) Phosphorus sources in all forms (manure, compost, rock, etc.) are optimized and appropriately used (e.g., using virgin-phosphate rock in pharmaceuticals to avoid potential contamination from other things).

Q8. **Big Idea:** ***Scales of Phosphorus***

Summary: When defining phosphorus sustainability, it should address phosphorus at different geographical scales (local, regional, national).
Exemplary Supporting Statements:
1) Maintaining self-sufficiency of phosphorus supply for agriculture and industry on local and global levels.
2) Sustainability of a particular nation, region, socioeconomic system, or global human society.
3) The ability to generate circular flows of phosphorus at local (e.g., a farm), regional (e.g., watershed), and national (e.g., country) scales.

Q9. **Big Idea:** ***Sustaining and Improving Food Production***
Summary: When defining phosphorus sustainability, it needs to emphasize developing management practices and/or technologies that will allow agricultural industries worldwide to have sufficient access to phosphorus to produce food.
Exemplary Supporting Statements:
1) Involve stakeholders with new food production approaches where phosphorus use may be more sustainable and/or utilize indigenous farming knowledge to improve the sustainable use of phosphorus in food production.
2) The capacity to access sufficient P to feed people equitably.
3) Optimizes phosphorus use in the production of proteins and carbohydrates for food production.

Part 2: Key Concepts for Understanding Phosphorus Sustainability

For the following "big ideas," please rate the level of importance (not important to extremely important) of each idea in relation to the following question: *"How important is teaching this idea in order to understand phosphorus sustainability?"*

Q10. **Big Idea:** ***Economic Factors of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to know the influences and impacts of phosphorus management on economies.
Exemplary Supporting Statements:
1) A person should know the economics associated with the sourcing, using, and environmental harm of phosphorus.
2) Understanding the technological and economic impacts across phosphorus' life cycle (from mining, use by humans, disposal, run-off) and the technological and economic challenges associated with mismanagement and run-off (e.g., costs associated with remediating a eutrophic lake).
3) Market failure is important to understand because it occurs when there are costs or benefits associated with an economic activity (such as agriculture) that are not reflected in the market price. This leads to an inefficient allocation of resources (such as phosphorus) because the harmful costs to society (water pollution) are not reflected in the cost of phosphorus, keeping the price too low and leading to less efficient use.

Q11. **Big Idea:** ***Environmental Impacts of Phosphorus***
Summary: To understand phosphorus sustainability, people need to understand the role of phosphorus in the environment, including the impacts of having too much or too little.
Exemplary Supporting Statements:
1) An important concept to be aware of is nutrient limitations in aquatic systems and the consequences of nutrient imbalances and excess loading of phosphate.
2) Knowledge of the environmental effects of P, especially eutrophication, and an understanding of the different roles of P and N in freshwater versus marine environments.
3) Knowledge of eutrophication and how water bodies are degrading by amplified inputs of nutrients.
4) Awareness of ecosystem ecology. One should understand biotic and abiotic processes that affect the flow of P in and between ecosystems. Aquatic systems are particularly important given how eutrophication affects their functioning.

Q12. **Big Idea:** ***Social Factors of Phosphorus***
Summary: To understand phosphorus sustainability, people need to comprehend the social implications and considerations (ethical, justice, equity, etc.) of phosphorus.
Exemplary Supporting Statements:
1) It is important to know societies need fair allocation and use of resources. No community should be able to dominate the use of a resource to the detriment of another community simply because one community is more powerful or affluent than another.
2) One should know the societal and ethical impacts of P management and use. This includes understanding the societal/ethical implications of mining P, the societal/ethical impacts over its lifecycle (e.g., from mining to use to disposal, run-off), and the societal/ethical challenges of its mismanagement and run-off (e.g., disproportional impacts of eutrophication, harmful algal blooms across different communities).
3) It is important to know the individual actions a person can take to decrease the demand for mined phosphate (e.g., reducing food waste or diet choices).

Q13. **Big Idea:** ***Anthropogenic Impacts to Phosphorus Cycle***
Summary: To understand phosphorus sustainability, it is essential to be aware of humanity's role in disrupting/changing the biogeochemical cycle of phosphorus.
Exemplary Supporting Statements:
1) A basic understanding of the nature and history of phosphorus and how humans have impacted the phosphorus cycle is needed. For example, how humans' use of phosphorus has impacted agricultural production, impacts of human fertilizer application, global food markets, etc.
2) A key concept is understanding anthropogenic disruptions to the phosphorus cycle and their consequences. This will highlight how humans have altered the natural biogeochemical cycles and the consequences of those disruptions, particularly in water quality.
3) To understand impacts and solutions, an individual should know the flows of phosphorus through the anthropogenic phosphorus cycle to understand impacts and solutions.

Q14. **Big Idea:** ***Geopolitics***

Summary: To understand phosphorus sustainability, it is important to recognize how phosphorus management is a geopolitical challenge because phosphate rock is located only in certain parts of the world, making its distribution and access volatile.
Exemplary Supporting Statements:
1) A critical concept for understanding phosphorus sustainability is international relations. This is important because global markets influence the price of phosphate rock/synthetic fertilizers, which can create pressures and opportunities and drive inequities in who uses what kind of P and when.
2) A person should be aware of the effects of cartels, market power, and international commodity markets because natural finite resources that are only mined in a few locations can be subject to oligopoly (market power). This allows producers to manipulate the price by changing how much is produced. The more the world depends on mined finite phosphorus, the more market power those few producers will enjoy.
3) The scarcity of phosphate rocks around the world has led to geopolitical situations.
4) It is important to consider the potential impacts that less reliance on phosphate rock can have on destabilizing regional or national politics, which could lead to unintended consequences such as more inequity.

Q15. **Big Idea:** ***Mass Balances ("P Flow Diagram")***
Summary: To understand phosphorus sustainability, it is essential to understand its input, output, and distribution throughout different systems. Mass balances are necessary for demonstrating the conservation of mass in phosphorus systems.
Exemplary Supporting Statements:
1) An important concept is phosphorus sources and flows because a person should understand where this finite resource comes from and where it goes
2) A person should understand nutrient budgets and mass balances at multiple scales (e.g., watershed to global) because it is important to know where phosphorus comes from, who is using it, where are the major losses, and how these balances vary globally.
3) P flow diagrams are important because phosphorus is present in an array of otherwise seemingly disparate processes across both the natural world and human-made infrastructure systems.
4) The skill of completing a mass balance is essential. Tracking the inputs of phosphorus, the reactions, and outputs of any system (e.g., farm, lake, wastewater facility) can help determine if phosphorus circularity is achieved or not. Mass balances involve defining the boundaries of a system, quantifying all of the inputs and outputs, and identifying any reactions that can increase or decrease the species of interest (in this case, the species would be phosphorus).

Q16. **Big Idea:** ***Phosphorus Cycle***
Summary: To understand phosphorus sustainability, a person must understand how phosphorus cycles in ecosystems (e.g., the nutrient/biogeochemical cycle of phosphorus and how phosphorus naturally circulates and moves through the world).
Exemplary Supporting Statements:
1) The concept of P cycling and the major sources and sinks of P need to be better taught. Understanding the processes of weathering, erosion, transport, deposition, biological uptake, and recycling is crucial for knowing where steps can be taken to improve sustainability. Unlike the C

and N cycles, the P cycle gets much less attention in both research and education. Enhancing P cycling education is important for increasing understanding of the fate and transport of P in the environment because it provides a framework for understanding the impacts of P management decisions.
2) The P cycle should be clearly defined and described to understand phosphorus sustainability.

Q17. **Big Idea:** ***Essential Element***
Summary: To understand phosphorus sustainability, it is important to know that all living things need phosphorus and that it is a nutrient living things have to get from external sources. Life can not continue without phosphorus; no substitute/alternative forms exist.
Exemplary Supporting Statements:
1) A person should understand the importance of P as an essential nutrient for plants and animals.
2) It is important to know the essential nature of P compounds for all organisms, from ATP for energy to phospholipids and lipoteichoic acids in cell walls and RNA and DNA. It is not possible to substitute any other element for P in these compounds.
3) Understanding phosphorus as a nutrient is essential because phosphorus is one of the building blocks of life. It is needed for all living things to grow (for better, as in crops, and worse, as in cyanobacteria).

Q18. **Big Idea:** ***Soil Sciences***
Summary: Knowing how phosphorus behaves in soil and the importance of soil health is important to understand phosphorus sustainability. One should be aware that phosphorus can build up in soils ("residual phosphorus") due to the continuous application of fertilizers beyond what plants actively need.
Exemplary Supporting Statements:
1) An important concept is understanding that much of the P in the soil is unavailable to plants and that applied P can quickly be tied up in the soil.
2) It is important to understand how phosphorus behaves in soils. People should know what happens when fertilizer is applied to soil in the short and long term, how "residual" phosphorus can be utilized, and what the role of organic phosphorus in soils is.

Q19. **Big Idea:** ***Sustainable Solutions***
Summary: To understand phosphorus sustainability, it is important to understand the solutions (e.g., management practices, technologies, consumer changes, etc.) that will allow for the more sustainable use of phosphorus.
Exemplary Supporting Statements:
1) It will be especially important not to overemphasize technical solutions to problems that can be addressed by implementing already available policies and practices (e.g., technology as a political suppression tactic).
2) It is important to know about appropriate technology. Technology that fits the needs of the users and is effective and affordable. The challenges in the global South are very different than those in the global North - there will not be a one-size-fits-all tech.
3) People need to Understand the pathways and obstacles to implementing solutions.

Q20. **Big Idea:** ***Recovery and Recycling of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to understand the role that recovering and recycling phosphorus will have in the sustainable use of phosphorus.
Exemplary Supporting Statements:
1) An important concept is to know how phosphorus is currently being recycled and reused (e.g., composting to removal from wastewater treatment).
2) Understanding opportunities for recovering phosphorus from residue streams is important. Many technologies exist to recover phosphorus from residue streams, which can then be used to create new products to facilitate phosphorus recycling (e.g., recycled fertilizers)
3) It is important to know strategies for recycling phosphorus on farms and minimizing losses to the environment.
4) Recycling phosphorus from wastewater and other waste streams is important for understanding phosphorus sustainability.
5) One should be aware that there will always be losses in the phosphorus cycles, and while recycling can help prevent loss, it will never eliminate loss from occurring.

Q21. **Big Idea:** ***Sources of Phosphorus***
Summary: To understand phosphorus sustainability, it is important to know the different sources of phosphorus (e.g., waste, soil, water systems, phosphate rocks/mines, etc.) and to recognize the difference between available phosphorus resources and reserves.
Exemplary Supporting Statements:
1) Recognition that there are other P sources than fertilizer and that their contribution to a sustainable agricultural sector needs to be taken into account.
2) An understanding of phosphorus reserves, resources, and uses. Most phosphorus inputs used by society come from finite reserves of phosphate rock located in only a few countries.

Q22. **Big Idea:** ***Systems Thinking***
Summary: To understand phosphorus sustainability, it is important to analyze phosphorus from a holistic approach that emphasizes all the interrelated parts of the phosphorus system and how it functions over time within the context of other systems (e.g., climate change, geopolitical/social/economic factors).
Exemplary Supporting Statements:
1) Systems thinking, which is the capacity to make connections among system features that might be different in nature, identify feedback loops, and generally acknowledge complexity, is a key skill for understanding phosphorus sustainability. Many decisions about P affect other issues, and other issues affect P. Without a systems understanding, interventions are likely to be ineffective.
2) An important skill is a synthesis view of P as part of a complex social-ecological-technological system and explores options, opportunities, trade-offs, and obstacles around a fundamental transformation of the P system toward sustainability. This is an advanced look at the potential for P transformation to allow people to interrogate and propose solutions at a system level.

Q23. **Big Idea:** ***Transdisciplinary Thinking***

Summary: To understand phosphorus sustainability, it is important to understand, combine, and utilize different disciplinary knowledges that play a role in phosphorus sustainability.
Exemplary Supporting Statements:
1) Transdisciplinarity is a key skill because it is important to know how to combine different disciplinary knowledge and 'other' forms of knowledge.

Q24. **Big Idea:** ***Wicked Problems***
Summary: To understand phosphorus sustainability, it is important to know that achieving phosphorus sustainability is challenging because there are alot of connecting factors from other sustainable development challenges (e.g., climate change).
Exemplary Supporting Statement:
1) The concept of wicked problems is essential because P sustainability is a highly complex, interdependent problem where our efforts can have unintended consequences that might fall into our blind spots.

Q25. **Big Idea:** ***Waste Systems***
Summary: To understand phosphorus sustainability, it is important to understand the role and impact of waste systems in managing phosphorus.
Exemplary Supporting Statements:
1) A key concept is knowledge of the anaerobic digestion process and how it affects the solubilization of P from human and animal wastes.
2) Understanding Biological Nutrient Removal (BNR) in sewage treatment, such as the Bardenpho process.
3) Knowledge of crystallization technologies for removing P from anaerobic digester filtrate and other wastewaters, especially struvite crystallization.
4) An important concept is sanitation/organic waste management engineering. Understand system options and functioning and how different contexts may require different options to treat excreta, food waste, and yard waste not only for P but also to be socially, economically, and environmentally desirable.
5) We need people to design new wastewater and organic matter recycling technologies. Some waste products high in P are inevitable and need to be managed and recycled; thus, organic waste management is key to P's sustainability.

Q26. **Big Idea:** ***Fertilizers***
Summary: To understand phosphorus sustainability, it is important to know the role fertilizers play in phosphorus systems, how fertilizers are made, why we need fertilizers, and current fertilizer practices and usage.
Exemplary Supporting Statements:
1) A key concept is phosphorus fertilizers. One should know the pros and cons of organic and inorganic sources of P, controlled-release, soluble granular, and liquid-applied P fertilizers, and their individual implications on crop productivity, P use efficiency, and runoff/leaching potential.
2) A key concept is understanding the central role of fertilizer in maintaining high yields.
3) It is important to know the issues associated with over-fertilization in the Global North (e.g., the oversupply of organic sources of P leading to the overproduction of beef and dairy).

Q27. **Big Idea:** ***Phosphorus in Agriculture***
Summary: To understand phosphorus sustainability, it is important to know the role phosphorus plays in agriculture systems (e.g., meeting the nutritional needs of livestock and crops) and the impacts agriculture has on the phosphorus cycle.
Exemplary Supporting Statements:
1) Understanding the opportunities for better phosphorus use in agriculture. There are many opportunities to improve phosphorus use efficiency in agriculture, underpinned by the concept of circular economies.
2) People should understand the role of phosphorus in raising livestock.
3) A key concept is the agricultural science regarding phosphorus. For example, the efficiency of its uptake in crops and harvest and an understanding of leaching and erosion losses of P from agricultural activity.
4) People should know how our current agricultural system works (e.g., moving P through the environment, contribution to excess P and its impacts).
5) Knowing the need to replenish nutrients removed by agricultural harvests is important.
6) An important concept is reducing phosphorus losses from agriculture. Loss of phosphorus from soil systems requires knowledge and skills around P transport and connection of crop fields to waterways through transport pathways.

Q28. **Big Idea:** ***Food Systems***
Summary: To understand phosphorus sustainability, it is important to know the role phosphorus plays in the ability to feed people.
Exemplary Supporting Statements:
1) An understanding of the relationship between phosphorus, food systems (the production, processing, distribution, and consumption of food), and food security. The availability of phosphorus to farmers is essential for food security.
2) Knowing the role P plays in the human diet is important.

Appendix D

Phosphorus Sustainability Education Interview Protocol:

Participant Background Information

1. What is your disciplinary background and training?

2. How long have you been involved in phosphorus sustainability research?

3. How did you get involved in phosphorus sustainability?

    a) What events led you to work in phosphorus sustainability?

    *if they are a member of an organization:

    b) How has joining a phosphorus sustainability organization(s) impacted your research? [*probe if they could have achieved their research accomplishments without being in these organization(s)]*

Conceptualization of Phosphorus Sustainability

4. What does phosphorus sustainability look like?

5. How has your conception of phosphorus sustainability changed throughout your career?

6. What are the root causes of unsustainable phosphorus development?

a) Do you think it is important for educators to address these root causes with their students/audiences when teaching about phosphorus sustainability? (probe why)

7. What are the consequences of not achieving phosphorus sustainability?

a) How should educators inform students/audiences of the consequences of not addressing phosphorus sustainability so that it doesn't create feelings of doom and gloom in students/audiences?

8. How is phosphorus sustainability different from other types of sustainable development challenges? (e.g., energy, water, climate change)

9. When you think of achieving phosphorus sustainability for future generations, what does that look like in 5, 25, and 100 years?

Phosphorus Sustainability Education

10. What challenges are we currently facing in addressing phosphorus sustainability that we should be preparing the next generation of students for?

11. What phosphorus sustainability issues stand out to you from the past, present, and future that educators should address with students/audiences?

12. What are the priorities for educating….

a) the current general population regarding phosphorus sustainability?

b) current students regarding phosphorus sustainability?

13. How can educators play a role in affecting change in human phosphorus practices and consumption?

14. What are the educational challenges for teaching and learning about phosphorus sustainability?

15. What lab, field, or other types of hands-on learning experiences, if any, are important for learning phosphorus sustainability?

16. As we work together to address phosphorus sustainability, how do we engage students and/or audiences across different generations, cultures, places, and disciplines?

17. Educators are already tasked with teaching students a curriculum jam-packed with important topics. Instead of adding new units to their curriculum specifically on phosphorus sustainability, where in current education topics (e.g., mining, biogeochemical cycles, eutrophication) do you think educators can begin adapting or incorporating phosphorus education into?

Appendix E

Qualitative Interview Study Codebook

Code Name	Definition	Exemplary Quotes
Agriculture and Food	Participant discusses phosphorus or phosphorus sustainability within the context of the agriculture industry (e.g., fertilizer application on farms) or food/food systems (e.g., the role phosphorus plays in feeding humans).	"I would hope that we had better adoption of currently available nutrient management practices in agriculture than they are much more widespread than they currently are, because they're all available, and they just need to be adopted."
Awareness	Participant discusses the need to raise awareness among people about phosphorus sustainability or the lack of awareness of the phosphorus sustainability issue.	"I think people can raise awareness about it by basically using it, I think it's such a great lens and example to show a lot of issues"
Background with Phosphorus	Participant shares their prior experiences/background working with phosphorus or phosphorus sustainability.	“And then my master's, someone ended up talking about phosphorus. And it was just a element that I think fit kind of my interests in trying to understand how we can better understand and treat the environment, but without excluding that human component that we know is so important.”
Challenges	Participants describes the challenges associated with phosphorus sustainability; including developing/implementing solutions, teaching or learning about phosphorus sustainability or achieving phosphorus sustainability.	"This idea of this linear thinking really permeates also the way that we educate. We want like bundles that are like, 'Okay, we've addressed the issue and not showing all the connections, because that's just too much.' So I think that's a really big challenge."

Code Name	Definition	Exemplary Quotes
Collaboration	Participant discusses collaborating or working with others when addressing phosphorus sustainability.	"So in that sense, once I started doing that work, it changed a lot of what I the type of work that I do, because it took me out of the lake, where I'd done 95% 90% of my work prior previous to that and brought me doing all kinds of other things in collaboration with these other disciplines"
Complexity	Participant mentions phosphorus sustainability as a complex/difficult topic and or shares examples of how/why phosphorus sustainability is complicated	"So it's a very, very complex problem that we're facing."
Concepts/Traits	Participant discusses concepts, traits or factors they consider to be associated with phosphorus sustainability.	"And then another factor, which is I think, insufficiently studied in sustainability science, in general is overall population"
Conceptual Change	Participant shares how their views of phosphorus sustainability have change over time.	"To be honest, before I started working on phosphorus, I didn't know a terrible amount about it. And, you know, so there's been definitely been a shift there. And it's something I'm very, very aware of now. And the importance of what it means for water quality, and living in the UK where all the rivers are below good status right now."
Consequences	Participant shares consequences of unsustainable phosphorus usage.	"I mean, the most immediate ones are deterioration and training water supplies and such"

Code Name	Definition	Exemplary Quotes
Educational Recommendations	Participants provides recommendations or suggestions in regards to teaching or learning phosphorus sustainability.	"I think it comes back to tailoring the message to the receiver, you know, so you know, a high school student isn't going to have is going to respond in the same way as somebody who's retired, you know, and they're not going to respond to the same information sources, and the same kinds of messaging. "
Empower	Participant discusses empowering people to take actions that can assist in achieving phosphorus sustainability or motivating people that they have influence on phosphorus sustainability solutions.	"You need to empower students, you need to empower educators, you need to provide clear solutions to these problems. You need to get everybody on the same page and talking about the problems in it, even if they have different solutions, you know, having a shared baseline, that there is a problem and the rough."
Equity/Justice/Fair	Participant discusses the importance/need for equitable, fair access to phosphorus for everyone or developing solutions that are fair to members of society (businesses, average citizens, etc.).	"I think the defining features of that future have to do with like, equitability of access"
Example/Tool	Participant discusses providing phosphorus sustainability learning to students or people by using it as a "tool" (e.g., an example, model, case study, etc.) to introduce/teach on other educational topics (e.g., mining, biogeochemical cycles).	"You know, you can talk about mining, toggle, biochemical, geochemical cycles, and the phosphorus in that. And you could definitely explain how this connects to that other unit, you're learning with phosphorus and two. So it's, it's, it's just being able to incorporate it into what maybe is already there, but also being able to articulate the connections between that so"

Code Name	Definition	Exemplary Quotes
Experiential Learning	Participant emphasizes learning phosphorus sustainability through meaningful participation and experiences ("learning by doing" or learning through doing and then reflecting on experience).	"So I view those structures as places where like, it's a great opportunity to like, test, you know, different technologies to have different menus, right to have kind of learning in multiple angles like that can allow people to experience a kind of experiential learning, kind of within those institutions."
Interdisciplinary	Participant discusses phosphorus sustainability from or needing to be approached from more than one branch of knowledge.	"So I think that the way to solve these problems is really in the middle, you know, you need to have people from the social science side of things, but you also need to have people who understand the, you know, hydrology, the chemistry, you know, the kind of like hard science and so I think, really being at the intersection of, for example, also not just look at crops, there is a big issue of manure, so you have to understand both livestock production and, crop production, and how they're connected or separated. And so I think the vision that we are trained to have is too narrow, to truly address the problem at the scale."
Interests	Participant discusses the importance of tailoring educational messages to individuals' interests (e.g., everyone needs food, what farmers care about will be different from what fisherman care about).	"And the thing that gets them all like, interested is food, talking about, you know, changing your diet, or were caring about where your food comes from, or thinking about the land use implications of diets, because we all eat, right. And so I think it's something where people can really see the connection between both their individual action and collective action. And all these environmental problems. So if you if you trace back, you know, like, this kind of diet has this kind of like implications for phosphorus sustainability. And that

Code Name	Definition	Exemplary Quotes
		also translates into water pollution, you know, translates into, you know, other all sorts of other problems that people can connect with."
Perspective	Participant discusses the importance of being able to view/acknowledge different perspectives.	"So I think it's like, understanding context, putting yourself in different people's shoes, and also being really curious about what might have worked or not work that you can maybe learn and adapt to your own context. And I think that that's the same across disciplines, right? Like, whatever. I'm talking to an agronomist, I don't know everything they're saying, whatever, it's very specific about their plant nutrient things. And I'm like, but like, what could I learn"
Politics/Policies/Regulations	Participant discusses the political implications of phosphorus sustainability, implications of current or future policies/regulations/practices in managing/utilizing phosphorus.	"You know, disruptive politics, it could eventually blow back and disrupt food systems, disrupt local countries is concerned, like, what happens if what happens to a place like Morocco and Western Sahara, if we don't need their phosphorus anymore?"
Root Causes	Participant shares causes of unsustainable phosphorus development/behavior.	"I would say that the root causes are that we have been in the global north, and in the US, in particular, I would say, you know, we have been promoting a kind of agricultural system, where the, we're consistently separating livestock and crop production and relying on external inputs."

Code Name	Definition	Exemplary Quotes
Science/Technology Solutions	Participant describes science and/or technology solutions to assist in achieving phosphorus sustainability.	"There are some tech fixes coming or at least out there possibly that you know, could get activated along the meat side of things or synthetic meat, artificial stem cell meat. Pretty exciting, whether it gets enough traction and scales the issue there, I think whether or not people are going to go for it or not. I also don't think everyone's going to become vegetarian anytime soon. So I do hope that the stem cell meat is successful."
Skills	Participant discusses the importance of teaching different skills that students and people can use (e.g., ability to collaborate, having critical thinking skills, developing systems thinking).	"So that's critical thinking skills come with like a base knowledge of how elements cycle in the world that's, like, so important in the classroom. And then the second one is like, yeah, the system's thinking component, but you're not really getting with the general public, it's more like, these are interlinked issues that we need to solve."
Social	Participant discusses phosphorus within the social implications and considerations one needs to consider, or discusses the social impacts of phosphorus or the social factors that have contributed to the unsustainable use of phosphorus.	“Well, there are a lot of interesting cultural aspects to this. I mentioned, for example, how Japan and China recycled human waste historically and about how Europe had to go to the Pacific Ocean to get their phosphorus…These are interesting, social, social issues surrounding these resources is the regional differences and, and how the regional differences have changed historically.”
Societal Solutions	Participant describes social solutions or behavioral changes that can be implemented/adopted/developed to assist in achieving phosphorus sustainability.	"So there are better practices for fertilizer management out there that could be implemented. There are. There's a lot of nutrient pollution associated with animal product production and animal husbandry, livestock rearing, and pigs and poultry. So that's a diet thing, right? So everyone

Code Name	Definition	Exemplary Quotes
		can adjust their own diets to reduce the amount of meat consumption that they that they have."
Solutions	Participant discusses the potential solutions that can be utilized or implemented to assist in achieving phosphorus sustainability that do no fit into any of the other specific solution codes (science/technology solutions and societal solutions)	"Happily, there are solutions, I think by which we can recover more phosphorus at the same time."
Systems Thinking	Participant describes the need to view phosphorus sustainability in terms of the whole picture and a variety of different relationships rather than by splitting it down into its parts.	"So educators have responsibility, you know, not just to teach people, you know, XY and Z, but also in the past, and possibly in the future, what has happened when X, Y, and Z were brought to bear? Or, you know, why does X y&z Not always accomplish what you think it should? Or help you do? What you think it would? I think educators have much, much more that have an obligation to explain the broader societal context and consequences of the knowledge that they're trying to convey"
Unique Trait(s)	Participants share unique traits that are associated with phosphorus sustainability (e.g., no gaseous state in phosphorus cycle) that distinguish it from other environmental related issues or science topics.	"There's no such thing as renewable phosphorus. There's no substitute for phosphorus."

Code Name	Definition	Exemplary Quotes
Waste	Participant mentions one of the several different waste (human waste, food waste, livestock waste) sources that phosphorus can be found in or discusses phosphorus sustainability in the context of waste (e.g., recycling phosphorus from animal manure)	"Other kinds of recycling like human waste recycling, or food waste recycling, a big factor would be reducing food waste. Food waste is one of the big drivers."