

## Research

# The phosphorus negotiation game (P-Game): first evaluation of a serious game to support science-policy decision making played in more than 20 countries worldwide

Nils Haneklaus<sup>1,37,38</sup> · Mary Kaggwa<sup>2</sup> · Jane Misihairabgwí<sup>3</sup> · Sherif Abu El-Magd<sup>4</sup> · Naima Ahmadi<sup>5</sup> · Jamal Ait Brahim<sup>6</sup> · Aloyce Amasi<sup>7</sup> · Andrea Balláné Kovács<sup>9</sup> · Łukasz Bartela<sup>10</sup> · Hajar Bellefqih<sup>11</sup> · Redouane Beniazza<sup>6</sup> · Jaroslav Bernas<sup>12</sup> · Essaid Bilal<sup>11</sup> · Tomislav Bituh<sup>13</sup> · Yelizaveta Chernysh<sup>14,15</sup> · Viktoriia Chubur<sup>14</sup> · Jelena Ćirić<sup>16</sup> · Claudia Dolezal<sup>17</sup> · Andrea Figulová<sup>18</sup> · Janja Filipi<sup>19</sup> · Gordana Glavan<sup>20</sup> · Tibor Guzsvinecz<sup>21</sup> · László Horváth<sup>22</sup> · Sasho Josimovski<sup>23</sup> · Martin Kiselicki<sup>23</sup> · Maja Lazarus<sup>13</sup> · Maja Kazazić<sup>24</sup> · István Komlósi<sup>9,39</sup> · Ali Maged<sup>4</sup> · Tebogo Mashifana<sup>25</sup> · Gordana Medunić<sup>26</sup> · Emina Mehić<sup>24</sup> · Felhi Mongi<sup>5</sup> · Kelvin Mtei<sup>7</sup> · Dennis Mwalongo<sup>7,8</sup> · Jerome Mwimanzu<sup>7,8</sup> · Jakub Nowak<sup>27</sup> · Oqba Basal<sup>39</sup> · Khaoula Qamouche<sup>1</sup> · Małgorzata Rajfur<sup>28</sup> · Hynek Roubík<sup>14</sup> · Mijalche Santa<sup>23</sup> · Cecília Sik-Lányi<sup>22</sup> · Maike Sippel<sup>29</sup> · Gerald Steiner<sup>1,30</sup> · Anna Skorek-Osikowska<sup>10</sup> · Anton Slavov<sup>31</sup> · Paweł Świsłowski<sup>28</sup> · Ali Tlili<sup>5</sup> · Kalina Trenevsk-Blagoeva<sup>23</sup> · Ivan Tschalakov<sup>32</sup> · Tomáš Vlček<sup>33</sup> · Stanisław Waclawek<sup>34</sup> · Ivan Zlatanović<sup>35</sup> · Matúš Mišík<sup>40</sup> · Hendrik Brink<sup>36</sup> · Tzong-Ru Lee<sup>37</sup>

Received: 24 September 2024 / Accepted: 19 November 2024

Published online: 02 January 2025

© The Author(s) 2024 **OPEN**

✉ Nils Haneklaus, nils.haneklaus@donau-uni.ac.at | <sup>1</sup>University for Continuing Education Krems, Dr.-Karl-Dorrek-Straße 30, 3500 Krems an der Donau, Austria. <sup>2</sup>Department of Environmental Science, Kyambogo University, Kampala, Uganda. <sup>3</sup>Human, Biological and Translational Medical Sciences, University of Namibia, Windhoek, Namibia. <sup>4</sup>Geology Department, Faculty of Science, Suez University, 43221 Suez, Egypt. <sup>5</sup>Department of Earth Sciences, University of Sfax, Sfax, Tunisia. <sup>6</sup>Institute of Science, Technology & Innovation (IST&I), Mohammed VI Polytechnic University (UM6P), 43150 Ben Guerir, Morocco. <sup>7</sup>Nelson Mandela African Institution of Science and Technology (NM-AIST), P.O. Box 447, Arusha, Tanzania. <sup>8</sup>Tanzania Atomic Energy Commission, P. O. Box 743, Arusha, Tanzania. <sup>9</sup>Institute of Agricultural Chemistry and Soil Science, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, Debrecen, Hungary. <sup>10</sup>Department of Power Engineering and Turbomachinery, Silesian University of Technology, 18 Konarskiego Street, 44-100 Gliwice, Poland. <sup>11</sup>Ecole Nationale Supérieure Des Mines de Saint Etienne, CNRS UMR, EVS, 5600, F42023 Saint Etienne, France. <sup>12</sup>Department of Agroecosystems, Faculty of Agriculture and Technology, University of South Bohemia in České Budějovice, Branišovská 1645/31A, 370 05 České Budějovice, Czech Republic. <sup>13</sup>Institute for Medical Research and Occupational Health, Zagreb, Croatia. <sup>14</sup>Department of Sustainable Technologies, Faculty of Tropical AgriSciences, Czech University of Life Sciences, 165 00 Prague, Czech Republic. <sup>15</sup>Department of Ecology and Environmental Protection Technologies, Sumy State University, Kharkivska Str., 116, Sumy, Ukraine. <sup>16</sup>Institute of Meat Hygiene and Technology, Kacanskog 13, 11040 Belgrade, Serbia. <sup>17</sup>Institute of Tourism, Department of Business, IMC Krems University of Applied Sciences, 3500 Krems an der Donau, Austria. <sup>18</sup>Faculty of Social and Economic Sciences, Comenius University Bratislava, Bratislava, Slovakia. <sup>19</sup>Department of Ecology, Agronomy and Aquaculture, University of Zadar, Trg Kneza Višeslava 9, 23000 Zadar, Croatia. <sup>20</sup>Department of Biology, Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, 1000 Ljubljana, Slovenia. <sup>21</sup>Department of Information Technology and Its Applications, Faculty of Information Technology, University of Pannonia, 8900 Zalaegerszeg, Hungary. <sup>22</sup>Department of Electrical Engineering and Information Systems, Faculty of Information Technology, University of Pannonia, Egyetem U. 10, 8200 Veszprem, Hungary. <sup>23</sup>Faculty of Economics, Ss. Cyril and Methodius University in Skopje, Skopje, Macedonia. <sup>24</sup>Dzermal Bijedic University of Mostar, 88104 Mostar, Bosnia and Herzegovina. <sup>25</sup>Department of Chemical Engineering, School of Mining and Chemical Engineering, University of Johannesburg, P O Box 17011, Doornfontein 2088, South Africa. <sup>26</sup>Faculty of Science, Department of Geology, University of Zagreb, Horvatovac 95, 10000 Zagreb, Croatia. <sup>27</sup>Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Mickiewicza 30 Av, 30-059 Kraków, Poland. <sup>28</sup>Institute of Biology, University of Opole, Kard. B. Kominka 6, 45-032 Opole, Poland. <sup>29</sup>HTWG Konstanz University of Applied Sciences, Alfred-Wachtel-Straße 8, 78462 Constance, Germany. <sup>30</sup>Complexity Science Hub Vienna, Josefstädter Straße 39, 1080 Vienna, Austria. <sup>31</sup>Department of Organic and Inorganic Chemistry, Technological Faculty, University of Food Technologies, 26 Maritsa Blvd., Plovdiv 4002, Bulgaria. <sup>32</sup>Department of Institutional and Applied Sociology, Paisii Hilendarski University of Plovdiv, Plovdiv, Bulgaria. <sup>33</sup>Department of International Relations and European Studies, Faculty of Social Studies, Masaryk University, Jostova 10, 60200 Brno, Czech Republic. <sup>34</sup>Institute for Nanomaterials, Advanced Technologies, and Innovation, Technical University of Liberec, Liberec, Czech Republic. <sup>35</sup>Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade, Serbia. <sup>36</sup>Department of Chemical Engineering, University of Pretoria, Pretoria 0002, South Africa. <sup>37</sup>Department of Marketing, National Chung Hsing University, Taichung, Taiwan. <sup>38</sup>Unit for Energy and Technology Systems - Nuclear Engineering, North-West University, Potchefstroom, South Africa. <sup>39</sup>Department of Applied Plant Biology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, Debrecen, Hungary. <sup>40</sup>Department of Political Science, Faculty of Arts, Comenius University Bratislava, Bratislava, Slovakia.



## Abstract

Environmental negotiations are complex, and conveying the interaction between science and policy in traditional teaching methods is challenging. To address this issue, innovative educational approaches like serious gaming and role-playing games have emerged. These methods allow students to actively explore the roles of different stakeholders in environmental decision-making and weigh for instance between sometimes conflicting UN Sustainable Development Goals or other dilemmas. In this work the phosphorus negotiation game (P-Game) is for the first time introduced. We present the initial quantitative and qualitative findings derived from engaging 788 students at various academic levels (Bachelor, Master, PhD, and Postdoc) across three continents and spanning 22 different countries. Quantitative results indicate that female participants and MSc students benefitted the most significantly from the P-Game, with their self-reported knowledge about phosphorus science and negotiation science/practice increasing by 71–93% (overall), 86–100% (females), and 73–106% (MSc students in general). Qualitative findings reveal that the P-Game can be smoothly conducted with students from diverse educational and cultural backgrounds. Moreover, students highly value their participation in the P-Game, which can be completed in just 2–3 h. This game not only encourages active engagement among participants but also provides valuable insights into the complex environmental issues associated with global phosphorus production. We strongly believe that the underlying methodology described here could also be used for other topics.

**Keywords** Environmental decision-making · Sustainable development goals · Phosphorus · Serious game · Teaching

## 1 Article highlights

- The Phosphorus Negotiation Game (P-Game) is for the first time introduced
- First results from playing in 22 countries with 788 participants are presented
- The P-Game can be played well with participants from various backgrounds

## 2 Introduction

In recent years, the integration of new teaching methods into traditional educational frameworks has introduced innovative and engaging approaches to learning across diverse disciplines. Among these approaches, serious games have gained prominence as effective tools for imparting complex concepts, fostering critical thinking, and enhancing decision-making skills [1, 2]. Recent reviews about the use of serious games in sustainable education are for instance provided by Hallinger et al. [3] and Stanitsas et al. [4].

The integration of serious games into educational curricula is a response to the growing recognition of the limitations of conventional pedagogical approaches. Traditional classroom settings often struggle to replicate the dynamic, unpredictable nature of real-world interactions [5–8]. As a result, students may find it challenging to grasp the intricacies of science-policy interfaces solely through theoretical instruction. Serious games, on the other hand, provide an experiential learning platform that mirrors the complexities of the real world while providing participants with the freedom to explore various decision pathways and observe the consequences of their choices in a controlled environment [9, 10].

Stokes and Selin [11] introduced the concept of the mercury game, a negotiation game that immerses participants in a scenario where they are tasked with making informed decisions in the context of science-policy interactions at Harvard Law School and the Massachusetts Institute of Technology at the beginning of the 2010s. Through this serious game, participants engage with real-world challenges related to environmental mercury contamination, allowing them to experience firsthand the complexities and dilemmas that policymakers often encounter. The study's evaluation of the mercury game shed light on its efficacy in enhancing the participants' understanding of the multifaceted nature of science-policy interfaces, ultimately emphasizing the potential of serious games in bridging the gap between scientific knowledge and its practical application in policy formulation. Serious games can thus be considered an important contribution to the emerging field of science diplomacy as pointed out by Mauduit and Soler [12].

Stokes and Selin [11] demonstrated the efficacy of the mercury game in enhancing participants' understanding of science-policy interactions, particularly in the context of environmental negotiations. Participants engaged in role-playing exercises that required them to balance scientific evidence, economic considerations, stakeholder interests, and ethical implications. The post-game evaluation indicated that participants not only developed a deeper appreciation for the intricacies of negotiating science-based policies but also emerged with improved negotiation skills and an

enhanced ability to navigate conflicting interests. Skills that can all be considered crucial competences in the field of environmental governance.

Inspired by the mercury game, we developed a serious game on sustainable phosphorus (P) production dubbed “P-Game”, or phosphorus negotiation game. Phosphorus is an essential element to all living beings. It is finite, and its mining as well as the processing of its ore is complex, affecting numerous, at times conflicting Sustainable Development Goals (SDGs) of the United Nations [13] so that several research groups have called for innovative approaches to improve our understanding of phosphorus production [14–16]. Following feedback from Stokes and Selin [11] the P-Game was played with students that have different educational (science and social science) as well as cultural backgrounds. In contrast to previous serious games [17, 18], our primary aim at this stage was not to provide additional education for experts of the phosphate industry. Instead, our focus was on assessing the effectiveness of the proposed game methodology, specifically, whether participants experienced an actual increase in knowledge and whether the serious game could be smoothly played without interruptions.

Playing serious environmental games often requires serious preparation of the participants ahead of the game that can take several weeks [19]. With the P-Game we wanted a much handier serious game that can be played within 2–3 h without any preparation of the participants ahead of the game. Such an approach seems to be typical for serious games in sales negotiations [20] or serious board games [21–23]. The rationale for keeping the duration of the P-Game relatively short served two purposes. Firstly, we aimed to create a game that could be seamlessly incorporated into existing courses, occupying no more than a single lecture (maximum 3 h). Secondly, we aimed for simplicity to enable the future digitization of the game, facilitating virtual play. Preliminary results for the virtual P-Game are currently under development, as outlined by Gyetvai et al. [24]. We believe that for a smartphone-based game, a shorter duration is essential to engage and attract participants effectively.

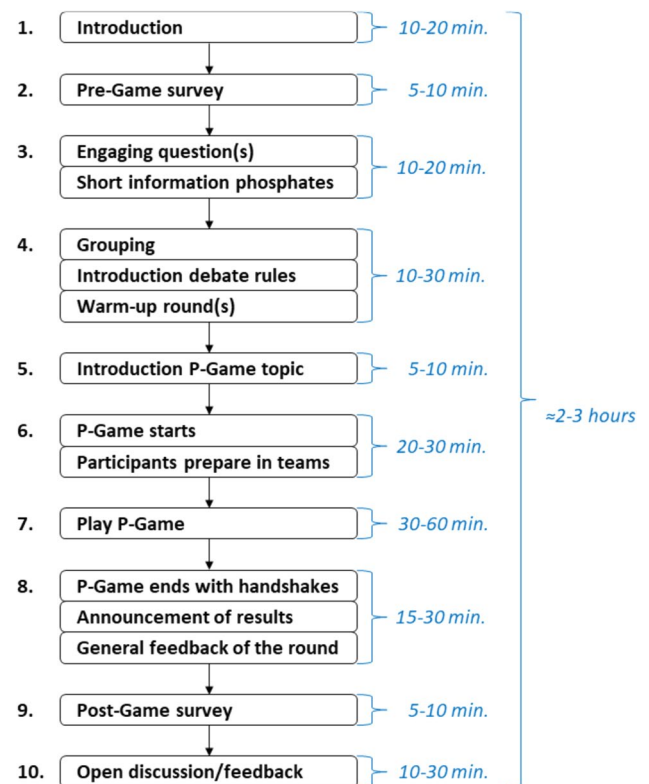
The objective of this publication is to provide an overview about the first set of qualitative and quantitative results obtained from playing the P-Game in 2022 and 2023. We further want to provide detailed information on how the P-Game was played so that others can use the underlying serious game methodology for their own work. The introduction provides a brief overview that discusses the motivation behind the development of the P-Game. The used P-Game methodology is subsequently introduced. Quantitative and qualitative results of the P-Game are presented and discussed. The overall conclusions as well as outlooks on the further planned developments of the P-Game are presented in the last chapter.

### 3 Methodology

Figure 1 provides an overview on how the P-Game was played at the different institutions. The participants were informed that they are going to participate in a role-playing game about cleaner fertilizer production, but they did not know that it would be about phosphorus. The lecture started with a short introduction of the moderator(s) conducting the P-Game, as well as some short information about the project that allowed for the development of the game. The short introduction (done with a projector and a slide deck) usually lasted 10–20 min and participants were subsequently handed pre-game surveys shown in Fig. 2 (left) that they were asked to fill out. The pre-game surveys together with the post-game surveys (Fig. 2 right) were used to collect the quantitative results and provided a chance for participants to openly comment on their expectations (pre-game surveys) and if these expectations were later met (post-game surveys). After the participants filled the surveys the moderator(s) would ask several open and engaging questions to all participants. The objective was to enhance the engagement of participants, particularly those who might be reserved, gain insight into their knowledge related to the phosphate industry and negotiation science/practice, and pinpoint individuals or groups among the participants who might be inclined to assume more significant roles in upcoming serious games. For instance, we regularly asked participants to estimate annual global phosphate ore production. Phosphate ore is the primary raw material used for phosphate fertilizer production. Following a minimum of three guesses, we would provide an explanation, often surprising the participants, that phosphate ore is indeed ranked among the five most extensively mined materials on earth and that there are significant uncertainties surrounding reported global phosphate ore production figures.

Geissler et al. [25] reported for instance discrepancies of up to 30% between phosphate ore production data provided by the United States Geological Survey, the British Geological Survey, the Austrian World Mining Data, the International Fertilizer Association, and CRU International. Indicating these uncertainties to participants was done to encourage them to take more active positions in the following P-Game and give them an idea about science policy, where conflicting opinions, “wicked problems”, and incomplete information is normal [26].

**Fig. 1** Overview on how the P-Game was played



Following the thought-provoking question, additional concise details were presented regarding the phosphate industry. The focus was on highlighting that phosphate ore is extracted for its phosphorus (P) content, a vital nutrient essential for plant growth. It was underscored that without the mining of phosphate ore, modern food production, as we have come to know it since the green revolution, would be unattainable. Since the amounts (approximately 200–300 million metric tons) of phosphate ore that are mined annually are considerable the phosphate industry also generates a relevant environmental footprint. This results in the introduction of a first dilemma between (i) the need of phosphate mining for mineral fertilizer and thus food production and (ii) the environmental impact this mining activity causes globally.

The engaging question(s) and short introduction to the phosphate industry (step 3 in Fig. 1) usually took between 10 and 20 min, and participants were subsequently divided into four groups for the following serious game. The participants were not only divided into four distinct groups but were also instructed to relocate, potentially necessitating a change in their seating arrangements. Following the grouping process, the concept of emulating a parliamentary setting with brief speeches (Fig. 3), adhering to the format of British Parliamentary Style (BPS) debating as previously recognized for its positive engagement by Eckstein and Bartanene [27], was introduced. Subsequently, a series of straightforward warm-up rounds were carried out, during which participants were tasked with elaborating on light-hearted topics for durations ranging from 10 to 30 s each. The motivation behind the warm-up rounds was to further engage the participants and assure that the format in which the subsequent P-Game would be conducted is understood.

Student debating knows many different formats, of which BPS originated in Liverpool in the mid-1800s, is the most popular one. In BPS debating, which establishes the guidelines for international university debating competitions like the World Universities Debating Championships, a proposition and opposition, mirroring a parliamentary debate in the House of Commons or House of Lords, involve Members of Parliament in discussing a predetermined motion. In our case the motion or topic of the debate was on sustainable phosphorus production/management. In BPS debating four teams consisting of eight speakers are trying to convince a group of judges (usually experienced debaters) of their allocated point of view. At competitive debate tournaments teams get 15 min to prepare ahead of the debate on a motion then given to them. The position of a team in a debate is decided by draw. Each speaker is then given the chance to present arguments in a 7-min speech during which the opposing teams can offer questions (called points of information since they do not necessarily have to be a question but could also be a remark) of a maximum duration of 15 s. Speakers are allotted the first and final minutes of each speech for the purpose of introducing and concluding their remarks, and these minutes cannot be used for posing questions. For the P-Game we used the format from BPS debating but shortened

**Pre P-Game Survey**

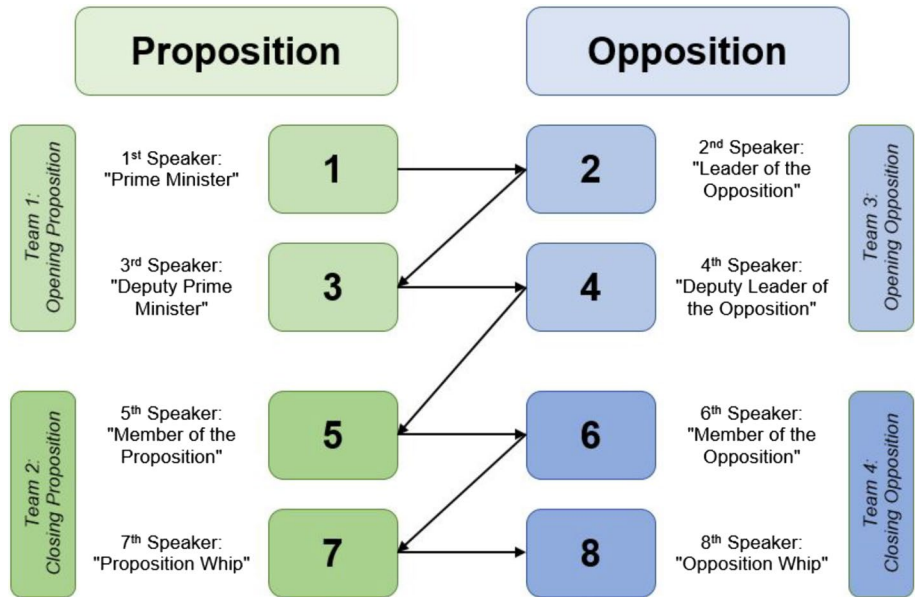
Do you consider yourself a science or social science student?	Science <input type="checkbox"/>		Social Science <input type="checkbox"/>		
What is your major?					
What is your level of education?	BSc-Student <input type="checkbox"/>	MSc-Student <input type="checkbox"/>	PhD-Student <input type="checkbox"/>	PhD Awarded <input type="checkbox"/>	
Gender	Male <input type="checkbox"/>	Female <input type="checkbox"/>		Other <input type="checkbox"/>	
Age group	<20 <input type="checkbox"/>	20-25 <input type="checkbox"/>	25-30 <input type="checkbox"/>	30-35 <input type="checkbox"/>	>35 <input type="checkbox"/>
Nationality					
Country of residence					
How would you rate your knowledge of Phosphorus Science? <small>(from 1, very poor/little – to 5 very good/much) – write number</small>	1	2	3	4	5
How would you rate your knowledge of Negotiation Science/Practice? <small>(from 1, very poor/little – to 5 very good/much) – write number</small>	1	2	3	4	5
Date					
What would you like to learn about Phosphorus Science and/or Negotiation Science/Practice? <small>(open answer)</small>					

**Post P-Game Survey**

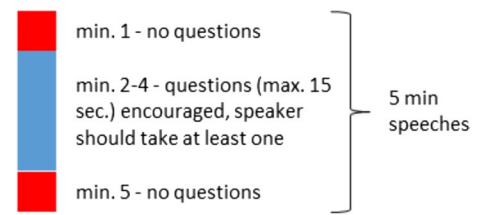
Do you consider yourself a science or social science student?	Science <input type="checkbox"/>		Social Science <input type="checkbox"/>		
What is your major?					
What is your level of education?	BSc-Student <input type="checkbox"/>	MSc-Student <input type="checkbox"/>	PhD-Student <input type="checkbox"/>	PhD Awarded <input type="checkbox"/>	
Gender	Male <input type="checkbox"/>	Female <input type="checkbox"/>		Other <input type="checkbox"/>	
Age group	<20 <input type="checkbox"/>	20-25 <input type="checkbox"/>	25-30 <input type="checkbox"/>	30-35 <input type="checkbox"/>	>35 <input type="checkbox"/>
Nationality					
Country of residence					
How would you rate your knowledge of Phosphorus Science? <small>(from 1, very poor/little – to 5 very good/much) – write number</small>	1	2	3	4	5
How would you rate your knowledge of Negotiation Science/Practice? <small>(from 1, very poor/little – to 5 very good/much) – write number</small>	1	2	3	4	5
How much and what do you think you learned about Phosphorus Science <small>(open answer)</small>					
How much and what do you think you learned about Negotiation Science/Practice? <small>(open answer)</small>					

**Fig. 2** Pre-and post-game surveys used for participants' self-assessments


**Fig. 3** Overview of British Parliamentary Style (BPS) Debating that provided a blueprint for the P-Game



**Fig. 4** Length of the speeches during the P-Game



**Fig. 5** Overview (also provided to the participants) of the dilemma chosen for the P-Game

<b>Proposition</b> for uranium recovery from phosphates		<b>Opposition</b> against uranium recovery from phosphates
<ul style="list-style-type: none"> <li>- Distribution of radiotoxic uranium with fertilizers can largely be mitigated</li> <li>- Recovered uranium could be used as a nuclear reactor fuel and reduce commercial uranium mining elsewhere</li> </ul>		<ul style="list-style-type: none"> <li>- Uranium recovery is presently not profitable due to the low uranium prices and can thus result in increased prices for fertilizers</li> <li>- Recovered uranium could be a nuclear proliferation risk</li> </ul>

the time of the speeches to 5 min as indicated in Fig. 4. We further gave the students more time (20–30 min) for the preparation of their speeches and allowed them to search for information on the deliberately chosen complex scientific topic online. During the P-Game teams consisted of a minimum of 2 participants that would give the speeches. Often there were more students in one team that supported the speakers in the preparation of their speeches. These students further engaged in the P-Game discussion by offering questions and we thus also asked them to fill out the pre- and post-game surveys.

Gamification in serious games is important to get participants engaged [28] and we thus also provided a ranking to the involved teams after the end of the discussion that was marked by a handshake between all participants. The handshake gesture held significance for us because, in the P-Game, students were tasked with representing viewpoints that might differ from their personal beliefs. Moreover, they were explicitly instructed not to concur with their counterparts. The gesture also clearly marked the end of the P-Game at which point the result (ranking of the teams) of the game was announced. The moderator(s) subsequently provided general feedback with regards to the presented arguments as well as the engagement between the teams with the other participants. This usually took between 15 and 30 min and participants were then asked to complete the post-game surveys and provide additional feedback to the moderator(s).

The motion or dilemma that was chosen for this first evaluation of the P-Game was the recovery of uranium during phosphate fertilizer production and participants were provided with first arguments for their contributions that is shown in Fig. 5.

The results from the pre- and post-game surveys as presented in Fig. 2 were analyzed using two standard statistical methods, two-way ANOVA and Hedges' *g* parameter. The two-way ANOVA has previously been applied in the pre- and post-game analysis of self-assessment surveys in game-based learning by Bilgin et al. [29]. Naeini [30] further used the method to understand the impact of self-assessments on language skills. The statistical methods are useful to determine the effects of the two independent variables (pre- or post-game and knowledge field—P-science or negotiation science) on a dependent variable (self-assessed knowledge). This provides the additional benefit that interaction between the variables as well as multi-comparison assessments can be done that provide additional insights into the obtained results [31]. The two-way ANOVA analyzes were done using the commercial software package GraphPad Prism 10 (GraphPad Software LLC, Boston, MA). To quantify the effect size of the pre- and post-game self-assessments as well as the self-assessed knowledge of the P-science in comparison to the negotiation science knowledge, the Hedges' *g* parameter was calculated [32]. This parameter has for instance previously been used to quantify the differences in subject knowledge pre- and post-playing of serious games by young people with chronic conditions [33], in psychological assessments [34], and the effects of self-assessments on academic performance [35]. The unbiased *g* parameter was calculated using Eq. "(1)" and Eq. "(2)".

$$g = J(n_1 + n_2 - 2) \frac{\bar{y}_1 - \bar{y}_2}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 - 1) + (n_2 - 1)}}} \tag{1}$$

$$J(a) = \frac{\Gamma\left(\frac{a}{2}\right)}{\sqrt{\frac{a}{2}}\Gamma\left(\frac{a-1}{2}\right)} \quad (2)$$

With  $n_i$  the size of the sample  $i$ ,  $\bar{y}_i$  the mean of the sample  $i$ , and  $\Gamma$  the gamma function.

The function  $J(n_1 + n_2 - 2)$  acts to unbiased the results for smaller sample sizes that tend to overestimate the effects. The numerator and denominator in the expression for  $g$  represent differences in means between the samples and the pooled standard deviations for the two samples, respectively. This means that  $g$  expresses the difference in means relative to the pooled standard deviation.

The interpretation of the magnitude of a Hedges'  $g$  value can vary depending on the context of the study and the field of research. However, there are some common conventions for interpreting the effect size represented by Hedges'  $g$  [32, 36]:

1. **Small Effect:** Typically, a Hedges'  $g$  value around 0.2 is considered a small effect size. This suggests a small but noticeable difference between groups or conditions.
2. **Medium Effect:** A Hedges'  $g$  value around 0.5 is often considered a medium effect size. This indicates a moderate difference between groups or conditions, which is typically considered meaningful.
3. **Large Effect:** Hedges'  $g$  values of around 0.8 or greater are generally considered large effect sizes. This suggests a substantial and significant difference between groups or conditions.

It is important to note that the interpretation of effect sizes should also consider the context of the study and the specific research question. Additionally, effect sizes should be interpreted alongside statistical significance tests (such as  $p$ -values) to provide a comprehensive understanding of the findings [37].

For instance, in the context of comparing means between two groups or conditions, a Hedges'  $g$  value can provide insight into the practical significance of the observed difference, while statistical significance tests indicate whether the observed difference is likely to have occurred by chance.

## 4 Results and discussion

### 4.1 Quantitative results

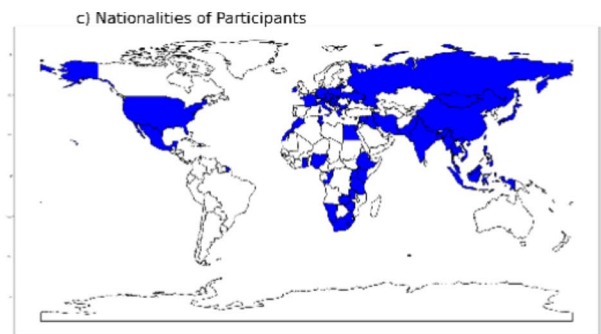
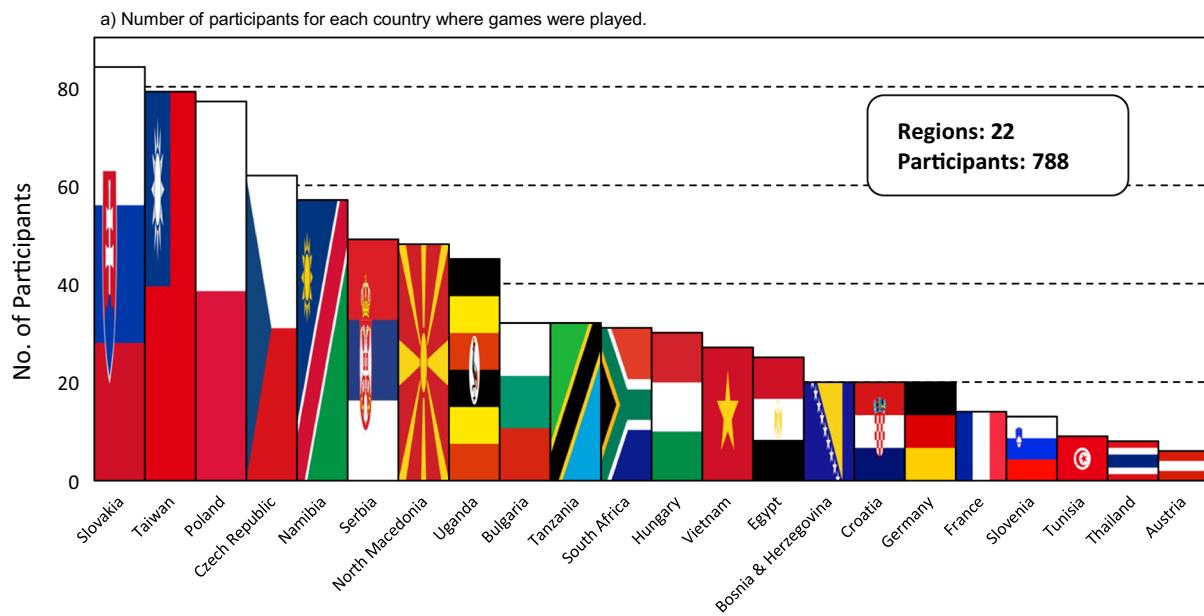
For this first evaluation of the P-Game methodology the serious game was played in 22 countries<sup>1</sup> by a total of 788 participants as depicted in Fig. 6a, b. The participants were also asked to self-report their nationalities and 58 nationalities<sup>2</sup> were reported (Fig. 6c).

Out of the 788 participants, 480 students (61%) reported that they are science students while the other 308 (39%) reported that they are majoring in social sciences. 89.7% of the participating students were either BSc-students (63.2% of total) or MSc-students (26.5% of total) with another 6.3% of the participants doing PhD studies, and 1.5% of the participants already having been awarded a PhD. 60.7% of the participating students were between 20–25 years old, and a relative balance between male (46.1%) and female (53.8%) participants could be achieved. The education background, education level, age and gender of the participating students is summarized in Table 1.

Following participation in the P-Game, participants were tasked with self-assessing their understanding of phosphorus science and negotiation science/practice through pre-and post-game surveys (see Fig. 2). The outcomes derived from these surveys underwent statistical analysis using two-way ANOVA and the Hedges'  $g$  parameter. The presented results

<sup>1</sup> Austria, Bosnia & Herzegovina, Bulgaria, Croatia, Czech Republic, Egypt, France, Germany, Hungary, Namibia, North Macedonia, Poland, Serbia, Slovakia, Slovenia, South Africa, Taiwan, Tanzania, Thailand, Tunisia, Uganda, Vietnam.

<sup>2</sup> Austria, Bangladesh, Belize, Bosnia and Herzegovina, Bulgaria, Cape Verde, China, Congo, Croatia, Czech, Egypt, Ethiopia, France, Germany, Ghana, Greece, Haiti, Hungary, Indian, Indonesia, Iranian, Iraq, Ireland, Italy, Japan, Kenya, Kingdom of Eswatini, Lebanon, Lesotho, Lithuania, Malaysia, Mexico, Mongolia, Moroccan, Myanmar, Nepal, Nigeria, Nigerian, Pakistan, Palau, Palestine, Philippines, Poland, Romania, South Africa, Russia, Rwanda, Serbia, Slovakia, Slovenia, South Sudan, Syria, Taiwan, Tanzania, Thailand, Tunisia, Uganda, Ukraine, United States of America, Vietnam, Zambia, Zimbabwe.



**Fig. 6** **a** Number of participants in the games as well as countries where the game was played, **b** Geographic distribution of countries where games were played, **c** Geographic distribution nationalities of participants

in Fig. 7 are categorized by participant demographics, including gender and academic qualifications (BSc, MSc, PhD, Post PhD), with accompanying brackets denoting the statistical significance of two-way ANOVA.

The findings reveal that, for most groups, there was no significant disparity in reported knowledge of P- or negotiation science/practice post-game. However, notable differences were observed in perceived knowledge between P- and negotiation science/practice pre-game among the total group, males, BSc, and MSc participants. Interestingly, all groups, except the Post PhD cohort, reported a significant increase (at the  $\alpha=0.05$  level) in knowledge for both categories when comparing pre- and post-game assessments. This observation underscores the substantial educational value gained from playing the P-Game across diverse participant groups.

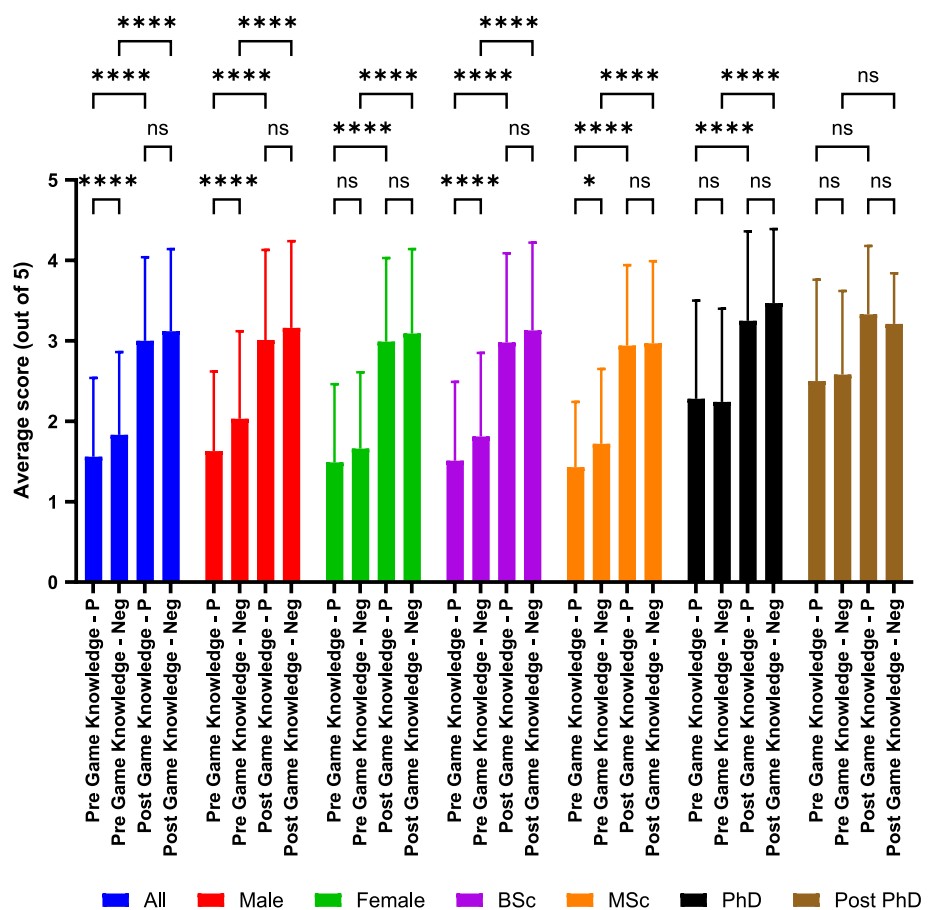
To gauge the magnitude of change or difference between means across various groups, the Hedges' *g* parameter presented in Table 2 was computed. The table should be interpreted both horizontally and vertically. Horizontally, the means  $\pm$  standard deviations for each group are reported concerning the subject field, while vertically, the pre- and post-game results are indicated in the columns. The resulting *g*-values for horizontal comparisons (rows) are displayed in the rightmost column, and the resulting *g*-values for each vertical comparison (columns within groups) are positioned below the reported results.

The Hedges' *g* values closely align with the outcomes of the two-way ANOVA, revealing nearly negligible differences in reported field knowledge post-game, with *g* values ranging from 0.01 to 0.1 (1% to 10% of the standard deviation). In contrast, the differences in knowledge of P- and negotiation science/practice for the combined group, males, BSc, and MSc students exceeded 16% of the standard deviation. Moreover, for the rows (pre- vs post-game results), significant increases in self-assessed knowledge were reported, with means surpassing 100% of the standard

**Table 1** Education background, education level, age and gender of the participating students

	Number	Share (%)
<b>Educational background</b>		
Science students	480	60.9
Social science students	308	39.1
<b>Education level</b>		
None indicated	19	2.4
BSc-Student	498	63.2
MSc-Student	209	26.5
PhD-Student	50	6.3
PhD awarded	12	1.5
<b>Age</b>		
< 20 years	102	12.9
20–25 years	478	60.7
25–30 years	87	11.0
30–35 years	44	5.6
> 35 years	69	8.8
<b>Gender</b>		
Male	363	46.1
Female	424	53.8

**Fig. 7** The reported average self-assessment scores for the pre- and post-game surveys with the standard deviation shown as error bars. The significance of the differences between Pre- and Post-game averages as well as the knowledge areas for the different groups were quantified by two-way ANOVA comparisons and expressed as the adjusted P-values (using the Tukey multi-comparison statistical hypothesis testing). The level of significance was indicated in brackets and annotated as: ns not significant  $p > 0.05$ , \*  $p = 0.033 - 0.05$ , \*\*  $p = 0.0021 - 0.033$ , \*\*\*  $p = 0.0001 - 0.0021$ , \*\*\*\*  $p < 0.0001$



deviations ( $g > 1$ ). These findings are consistent with previous research on the impact of serious games on knowledge enhancement, where  $g$  values between 0.1 and 1.0 were reported [33].

**Table 2** Results of the quantitative self-assessment concerning knowledge about phosphorus science and negotiation science/practice (n = 788)

	Pre-game self-assessments	Post-game self-assessments	Change (%)	Hedges' g parameter (horizontal)
<b>All (n = 788)</b>				
Knowledge about phosphorus science	1.56 ± 0.98	3 ± 1.04	+ 92.7	1.43
Knowledge about negotiation science/practice	1.83 ± 1.03	3.12 ± 1.02	+ 70.8	1.26
Hedges' g parameter (vertical)	0.16	0.04		
<b>Male (n = 359)</b>				
Knowledge about phosphorus science	1.63 ± 0.99	3.01 ± 1.12	+ 84.5	1.30
Knowledge about negotiation science/practice	2.03 ± 1.09	3.16 ± 1.08	+ 56.0	1.04
Hedges' g parameter (vertical)	0.21	0.05		
<b>Female (n = 420)</b>				
Knowledge about phosphorus science	1.49 ± 0.97	2.99 ± 1.04	+ 100.4	1.49
Knowledge about negotiation science/practice	1.66 ± 0.95	3.09 ± 1.05	+ 86.3	1.42
Hedges' g parameter (vertical)	0.10	0.03		
<b>BSc-Students (n = 490)</b>				
Knowledge about phosphorus science	1.51 ± 0.98	2.98 ± 1.11	+ 96.8	1.40
Knowledge about negotiation science/practice	1.81 ± 1.04	3.13 ± 1.09	+ 72.6	1.23
Hedges' g parameter (vertical)	0.18	0.05		
<b>MSc-Students (n = 209)</b>				
Knowledge about phosphorus science	1.43 ± 0.81	2.94 ± 1	+ 105.7	1.66
Knowledge about negotiation science/practice	1.72 ± 0.93	2.97 ± 1.02	+ 72.7	1.28
Hedges' g parameter (vertical)	0.18	0.01		
<b>PhD-Students (n = 50)</b>				
Knowledge about phosphorus science	2.28 ± 1.22	3.25 ± 1.11	+ 42.5	0.83
Knowledge about negotiation science/practice	2.24 ± 1.16	3.47 ± 0.92	+ 54.9	1.17
Hedges' g parameter (vertical)	0.02	0.06		
<b>PhD Awarded (n = 12)</b>				
Knowledge about phosphorus science	2.5 ± 1.26	3.33 ± 0.85	+ 33.3	0.75
Knowledge about negotiation science/practice	2.58 ± 1.04	3.21 ± 0.63	+ 24.2	0.70
Hedges' g parameter (vertical)	0.03	0.04		

The values reported for the Pre- and Post-game self-assessments are the average ± standard deviations

While most participants benefited from the P-Game, reporting increased knowledge in both phosphorus science and negotiation science/practice, self-assessments indicated that female participants and MSc students experienced the most significant gains. Notably, participating students expressed greater confidence in their understanding of negotiation science/practice compared to the more technical domain of phosphorus science. Lower reported knowledge levels in the pre-game surveys contributed to an overall more substantial self-reported increase in knowledge. Interestingly, only the group of PhD students exhibited a more significant increase in reported knowledge in negotiation science/practice compared to the increase in self-reported knowledge in phosphorus science.

## 4.2 Qualitative results

### 4.2.1 Overview

The P-Game received positive feedback from students, with most expressing satisfaction in their experience. They particularly enjoyed the interaction with their peers and the opportunity to apply their classroom knowledge in a competitive game, specifically on topics related to environmental and policy science. Most students would comment that the P-Game was "very interesting" and that they learned "a lot" about phosphorus science as well as negotiation science/practice.

While the nature of arguments in different rounds varied significantly based on the educational and cultural backgrounds of participating students, two overarching themes emerged as central to most P-Game rounds.

Students engaged in discussions surrounding (i) economics, processes, proliferation concerns, and worker safety related to uranium recovery from phosphates, and (ii) potential health risks associated with uranium in phosphates. In this work, we also provide scientific background information that was presented to the students during the feedback rounds following the games.

#### 4.2.2 Uranium recovery from phosphates (economics, processes, proliferation concerns, and worker safety)

Phosphate ores utilized in the production of mineral fertilizers can exhibit elevated levels of heavy metals, with cadmium being recognized as a potential health concern [38]. Additionally, radiotoxic uranium [39] and rare earth elements (REEs) [40, 41] can also be present in significant concentrations in phosphate ores worldwide. These ores can originate from either magmatic (igneous) or sedimentary sources, and they tend to exhibit varying concentrations of associated trace elements. In igneous phosphate ores, REEs can reach concentrations of up to 0.2 wt%, while sedimentary phosphate ores generally have lower concentrations. The global average REE concentration for phosphate ores is estimated to be around 0.05 wt% [42], considering that there are more sedimentary phosphate ore reserves than igneous ones. Sedimentary Moroccan phosphate ores account for over 70% of known reserves [43] and can contain uranium concentrations ranging from 0.01% to 0.02% [44], while uranium concentrations in magmatic phosphate ores are typically below 0.005% [45].

Though the concentrations of these elements in phosphate ores might be considered moderate at best, the potential quantities of both REEs and uranium that could theoretically be extracted are substantial, given the global annual mining of 200–300 million metric tons of phosphate ore. Phosphate ore ranks as one of the top five most extracted materials on earth and estimates by Hakkar et al. [46] suggest that the recovery of REEs from Moroccan phosphate ore mining alone could meet 7–15% of global demand. Furthermore, research by Zhang [47] indicates that the United States could fulfill its entire REE demand through the recovery of REEs during phosphate processing in Florida. Haneklaus [39] projected that uranium recovered during phosphate fertilizer production could have theoretically accounted for 16–26% (8,800–14,000 t) of the world's commercial uranium needs in 2018. More detailed estimations are available for individual countries/regions. In the United States around 2,116 t out of 20,386 t uranium requirements could have come from phosphates in 2014 [48, 49]. China could have theoretically been able to recover 648 t (about 10% of the country's uranium demand) during fertilizer production in 2016 [50]. In the European Union about 334 t uranium (approximately 2% of demand) could have theoretically been recovered from imported phosphate ores in 2017 [51], and in Argentina this number could be roughly 19 t (approximately 8% of the country's demand) in 2017 [52]. Additionally, Diwa et al. [53] estimated that 14–26 t of uranium (covering 12–21% of the projected near-term uranium demand) could be extracted from imported phosphate ores in the Philippines. Khan et al. [54] conducted similar calculations for domestically mined phosphate ores in Saudi Arabia and concluded that around 413–551 t (11–15% of the projected near-term natural uranium requirements) could be obtained during phosphate fertilizer production.

Currently, both REEs and uranium are not commonly recovered during phosphate fertilizer production. While industrial-scale uranium recovery from wet-phosphoric acid (WPA), an intermediate liquid product in phosphate fertilizer manufacturing, was practiced in Florida during the 1980s and 1990s. Declining uranium prices rendered this approach economically unviable [55]. Ye et al. [56] suggested that a coordinated recovery of uranium from the more than 400 fertilizer plants worldwide is unlikely to occur soon. Alternatively, the initiation of recovery operations could be prompted by economic incentives, coupled with the imperative to circumvent adverse consequences linked to heightened heavy metal content [57] or potential sales restrictions stemming from the introduction of uranium limits as a result of elevated uranium concentrations. The latter can for instance be observed in East Africa [58–61].

During the P-Game, the students' conversations frequently revolved around topics such as economics, the procedures involved in uranium recovery, safety measures for workers engaged in these processes, and potential proliferation concerns. These concerns were introduced as an argument in Fig. 5, which was presented to the students.

At present uranium recovery from phosphates is not economically viable, but various stakeholders (including commercial mining and fertilizer companies) are looking into this option to diversify and reduce supply risks. It can be argued (and a lot of students did this) that even though uranium recovery from phosphates is not economic today, subsidies could build momentum and encourage companies to further invest to develop processes that might be economically viable tomorrow. A mechanism that also successfully worked for solar photovoltaic. During these processes workers safety

is usually not of concern since measures as they are in place in a uranium mining operation today can be employed to protect personnel involved in the extraction process.

Uranium is one of the raw materials that can be used in the production of nuclear weapons, and potential nuclear proliferation concerns associated with uranium from phosphates are an active field of scientific discussion [62–64].

#### 4.2.3 Potential health risks associated with uranium in phosphate fertilizers

Extended use of phosphate rock and phosphate fertilizer results in uranium build-up on agricultural soils that is actively discussed by the scientific community [65–68]. There is particular concern regarding uranium accumulation since the metal is radiotoxic and can endanger soil fertility, leach into groundwater [69, 70], and be taken up by crops [71–74]. At present there is no legal limit for uranium in mineral fertilizers though some organizations such as the Soil Protection Commission of the German Federal Environment Agency (UBA) suggest formulating legal limits. Kratz et al. [75] report that the legal limit (50 mg uranium per kg  $P_2O_5$  for P containing fertilizers) suggested by UBA was exceeded by all 161 phosphate fertilizer samples the researchers investigated. Further analysis of 414 phosphate fertilizers used in Europe [76] reported similar uranium concentrations. The debate about a potential legal limit on uranium in mineral fertilizers is still ongoing with the European Parliament confirming that it is actively following scientific results on this topic [77]. The uncertainties surrounding the potential health risks associated with uranium from phosphate fertilizers applied to agricultural soils made for a great, balanced topic within the P-Game, and we could experience that participants with more elaborated negotiation skills would usually be able to decide this topic for their team.

## 5 Conclusions and outlook

This work provides a first overview of the phosphorus negotiation game (P-Game). Our experience with 788 students ranging from Bachelor's to Postdoctoral level across three continents and spanning 22 countries has taught us that the fundamental game methodology is well-suited for conducting serious games. Additionally, it has become evident that students are generally enthusiastic about the game, which provides them with an interactive opportunity to experiment with various roles. Further work will focus on offering a virtual version of the P-Game that will operate on a smartphone interface. The P-Game has already been incorporated in the curriculum of several participating universities and we plan to further refine the P-Game methodology and surveys, extend it to different topics such as sustainable energy production as well as other conflicting UN Sustainable Development Goals [78–80], and collect additional data from more specific sets of participants to better understand the specific learning mechanisms of the game. One focus area could for instance entail a comparison of results between students and groups of society outside of academia to see potential differences in how they play the game.

## 6 Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI and AI-assisted technology was used in the writing process.

**Acknowledgements** The authors want to sincerely thank all students participating in the P-Game for the lively, exciting, entertaining, and useful discussions. We further thank Prof. Gerald Steiner from the University for Continuing Education Krems for proposing the development of a serious game about phosphorus science, and thank the Federal Ministry of Education, Science and Research (BMBWF) and here specifically the implementing organization, Austria's Agency for Education and Internationalization (OeAD) for supporting the resulting Africa UniNet project P006 entitled: "The Phosphorus Negotiation Game—SDGs in Action" (P-Game).

**Author contributions** Nils Haneklaus: Conceptualization, Formal Analysis, Methodology, Investigation, Visualization, Funding acquisition, Writing—Original Draft, Mary Kaggwa: Conceptualization, Formal Analysis, Methodology, Investigation, Writing—Review & Editing, Jane Misi-hairabgwi: Conceptualization, Formal Analysis, Methodology, Investigation, Writing—Review & Editing, Sherif Abu El-Magd: Formal Analysis, Investigation, Writing—Review & Editing, Naima Ahmadi: Formal Analysis, Investigation, Writing—Review & Editing, Jamal Ait Brahim: Formal Analysis, Investigation, Writing—Review & Editing, Aloyce Amasi: Formal Analysis, Investigation, Writing—Review & Editing, Andrea Balláné Kovács: Formal Analysis, Investigation, Writing—Review & Editing, Łukasz Bartela: Formal Analysis, Investigation, Writing—Review & Editing, Hajar Bellefqih: Formal Analysis, Investigation, Writing—Review & Editing, Redouane Beniazza: Formal Analysis, Investigation, Writing—Review & Editing, Jaroslav Bernas: Formal Analysis, Investigation, Writing—Review & Editing, Essaid Bilal: Formal Analysis, Investigation, Writing—Review & Editing, Tomislav Bituh: Formal Analysis, Investigation, Writing—Review & Editing, Yelizaveta Chernysh: Formal Analysis, Investigation,

Writing—Review & Editing, Viktoriia Chubur: Formal Analysis, Investigation, Writing—Review & Editing, Jelena Ćirić: Formal Analysis, Investigation, Writing—Review & Editing, Claudia Dolezal: Formal Analysis, Investigation, Writing—Review & Editing, Andrea Figulová: Formal Analysis, Investigation, Writing—Review & Editing, Janja Filipi: Formal Analysis, Investigation, Writing—Review & Editing, Gordana Glavan: Formal Analysis, Investigation, Writing—Review & Editing, Tibor Guzvinecz: Formal Analysis, Investigation, Writing—Review & Editing, László Horváth: Formal Analysis, Investigation, Writing—Review & Editing, Sasho Josimovski: Formal Analysis, Investigation, Writing—Review & Editing, Martin Kiselićki: Formal Analysis, Investigation, Writing—Review & Editing, Maja Lazarus: Formal Analysis, Investigation, Writing—Review & Editing, Maja Kazazić: Formal Analysis, Investigation, Writing—Review & Editing, István Komlósi: Formal Analysis, Investigation, Writing—Review & Editing, Ali Maged: Formal Analysis, Investigation, Writing—Review & Editing, Tebogo Mashifana: Formal Analysis, Investigation, Writing—Review & Editing, Gordana Medunić: Formal Analysis, Investigation, Writing—Review & Editing, Emina Mehić: Formal Analysis, Investigation, Writing—Review & Editing, Felhi Mongi: Formal Analysis, Investigation, Writing—Review & Editing, Kelvin Mtei: Formal Analysis, Investigation, Writing—Review & Editing, Dennis Mwalongo: Formal Analysis, Investigation, Writing—Review & Editing, Jerome Mwimanzi: Formal Analysis, Investigation, Writing—Review & Editing, Jakub Nowak: Formal Analysis, Investigation, Writing—Review & Editing, Oqba Basal: Formal Analysis, Investigation, Writing—Review & Editing, Khaoula Qamouche: Formal Analysis, Investigation, Writing—Review & Editing, Małgorzata Rajfur: Formal Analysis, Investigation, Writing—Review & Editing, Hynek Roubík: Formal Analysis, Investigation, Writing—Review & Editing, Mijalche Santa: Formal Analysis, Investigation, Writing—Review & Editing, Cecília Sik-Lányi: Formal Analysis, Investigation, Writing—Review & Editing, Maike Sippel: Formal Analysis, Investigation, Writing—Review & Editing, Gerald Steiner: Conceptualization, Formal Analysis, Investigation, Writing—Review & Editing, Anna Skorek-Osikowska: Formal Analysis, Investigation, Writing—Review & Editing, Anton Slavov: Formal Analysis, Investigation, Writing—Review & Editing, Paweł Świsłowski: Formal Analysis, Investigation, Writing—Review & Editing, Ali Tlili: Formal Analysis, Investigation, Writing—Review & Editing, Kalina Trenevsk-Blagoeva: Formal Analysis, Investigation, Writing—Review & Editing, Ivan Tschalakov: Formal Analysis, Investigation, Writing—Review & Editing, Tomáš Vlček: Formal Analysis, Investigation, Funding acquisition, Writing—Review & Editing, Stanisław Waclawek: Formal Analysis, Investigation, Writing—Review & Editing, Ivan Zlatanović: Formal Analysis, Investigation, Writing—Review & Editing, Matúš Mišík: Formal Analysis, Writing—Review & Editing, Investigation Hendrik Brink: Conceptualization, Formal Analysis, Methodology, Validation, Writing—Original Draft, Investigation, Visualization, Tzong-Ru Lee: Conceptualization, Formal Analysis, Methodology, Investigation, Writing—Review & Editing.

**Funding** This work received support by the Federal Ministry of Education, Science and Research (BMBWF) through Austria's Agency for Education and Internationalization (OeAD) [Grant Numbers: Africa UniNet P006, P056 and P058, APPEAR Project341, KoEF 04/2019 and 01/2020, WTZ BA 04/2023, BG 01/2021, CZ 12/2024, CZ 13/2024, CZ 14/2022, FR 12/2024, HR 09/2022, HR 14/2024, HU 06/2022, HU 06/2024, PL 10/2022, PL 12/2024, MK 13/2024 and TW 01/2021]. APPEAR is a programme of the Austrian Development Organization. Besides, Technology Agency of the Czech Republic (TA CR) [Grant Number: TH79020003] support for this project is offered under the coordination of the ERA-MIN3 action, which has received funding from the European Union under the Horizon 2020 Program [European Commission Grant Agreement No. 101003575]. This work was further supported by the European Union – Next Generation EU projects EBDIZ and HumEnHealth [Program Contract of 8 December 2023, Class: 643-02/23-01/00016, Reg. no. 533-03-23-0006], the Ministry of Education, Youth and Sports of the Czech Republic [Reg. no.: 8J24AT037], the Ministry of Education and Science of the Republic of North Macedonia [Grant Number: 20-667/21], the Polish National Agency for Academic Exchange (NAWA) [Grant Number: BPN/ULM/2021/1/00137], the National Research, Development and Innovation Office of Hungary [Grant Numbers: 2021-1.2.4-TÉT-2021-00007 and 2023-1.2.4-TÉT-2023-00037], the Ministry of Civil Affairs of Bosnia and Herzegovina [Grant Number: 156/22] and the Slovak Research and Development Agency [Grant No. APVV-23-0032]. Part of this investigation was conducted within the facilities founded by European Regional Development Fund project KK.01.1.1.02.0007 "Research and Education Centre of Environmental Health and Radiation Protection – Reconstruction and Expansion of the Institute for Medical Research and Occupational Health.

**Availability of data and materials** The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Ethics approval and consent to participate** The nature of the research, the methods used, and the fact that no personal data was stored or can be traced back to individuals, conforming with GDPR standards, means that the study is not subject to an ethics permit. Freely-given and informed consent was obtained for each participant. They were reassured that their participation is voluntary and that they were free to withdraw at any time. In addition, all information was gathered anonymously and handled confidentially. The study design assured adequate protection of study participants, and neither included clinical data about patients nor configured itself as a clinical trial.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

## References

1. Rumore D, Schenk T, Susskind L. Role-play simulations for climate change adaptation education and engagement. *Nat Clim Chang*. 2016;6:745–50. <https://doi.org/10.1038/nclimate3084>.
2. Urcuqui-Bustamante AM, Selfa T, Ashcraft CM, Asbjornsen H, Jones KW, Manson RH, et al. Using science-based role-play simulations to inform payment for hydrological services program design in Mexico. *Environ Sci Policy*. 2023;139:71–82. <https://doi.org/10.1016/j.envsci.2022.10.016>.
3. Hallinger P, Wang R, Chatpinyakoo C, Nguyen VT, Nguyen UP. A bibliometric review of research on simulations and serious games used in educating for sustainability 1997–2019. *J Clean Prod*. 2020. <https://doi.org/10.1016/j.jclepro.2020.120358>.
4. Stanitsas M, Kirytopoulos K, Vareilles E. Facilitating sustainability transition through serious games: a systematic literature review. *J Clean Prod*. 2019;208:924–36. <https://doi.org/10.1016/j.jclepro.2018.10.157>.
5. Bates R, Brenner B, Schmid E, Steiner G, Vogel S. Towards meta-competences in higher education for tackling complex real-world problems—a cross disciplinary review. *IJSHE*. 2022. <https://doi.org/10.1108/IJSHE-06-2021-0243>.
6. Handelsman J, Ebert-May D, Beichner R, Bruns P, Chang A, DeHaan R, et al. Scientific teaching. *Science* (1979). 2004;304(5670):521–2. <https://doi.org/10.1126/science.1096022>.
7. Leal Filho W, Raath S, Lazzarini B, Vargas VR, de Souza L, Anholon R, et al. The role of transformation in learning and education for sustainability. *J Clean Prod*. 2018;199:286–95. <https://doi.org/10.1016/j.jclepro.2018.07.017>.
8. Leal Filho W, Brandli LL, Dinis MAP, Vidal DG, Paço A, Levesque V, et al. International trends on transformative learning for urban sustainability. *Discov Sustain*. 2023. <https://doi.org/10.1007/s43621-023-00145-7>.
9. Gugerell K, Zuidema C. Gaming for the energy transition. Experimenting and learning in co-designing a serious game prototype. *J Clean Prod*. 2017;169:105–16. <https://doi.org/10.1016/j.jclepro.2017.04.142>.
10. Khoury M, Evans B, Chen O, Chen AS, Vamvakieridou-Lyroudia L, Savic DA, et al. NEXTGEN: a serious game showcasing circular economy in the urban water cycle. *J Clean Prod*. 2023;391:136000. <https://doi.org/10.1016/j.jclepro.2023.136000>.
11. Stokes LC, Selin NE. The mercury game: evaluating a negotiation simulation that teaches students about science-policy interactions. *J Environ Stud Sci*. 2016;6(3):597–605. <https://doi.org/10.1007/s13412-014-0183-y>.
12. Mauduit JC, Gual SM. Building a science diplomacy curriculum. *Front Educ* (Lausanne). 2020. <https://doi.org/10.3389/educ.2020.00138>.
13. El Wali M, Golroudbary SR, Kraslawski A. Circular economy for phosphorus supply chain and its impact on social sustainable development goals. *Sci Total Environ*. 2021. <https://doi.org/10.1016/j.scitotenv.2021.146060>.
14. Stamm C, Binder CR, Frossard E, Haygarth PM, Oberson A, Richardson AE, et al. Towards circular phosphorus: the need of inter- and transdisciplinary research to close the broken cycle. *Ambio*. 2021. <https://doi.org/10.1007/s13280>.
15. Scholz RW, Steiner G. The role of transdisciplinarity for mineral economics and mineral resource management: coping with fallacies related to phosphorus in science and practice. *Miner Econ*. 2022;35(3):745–63. <https://doi.org/10.1007/s13563-022-00331-5>.
16. Iwaniec DM, Metson GS, Cordell D. P-FUTURES: towards urban food & water security through collaborative design and impact. *Curr Opin Environ Sustain*. 2016;20:1–7. <https://doi.org/10.1016/j.cosust.2016.03.001>.
17. Hossard L, Schneider C, Voltz M. A role-playing game to stimulate thinking about vineyard management practices to limit pesticide use and impacts. *J Clean Prod*. 2022. <https://doi.org/10.1016/j.jclepro.2022.134913>.
18. Spitters HPEM, van de Goor LAM, Lau CJ, Sandu P, Eklund Karlsson L, Jansen J, et al. Learning from games: stakeholders' experiences involved in local health policy. *J Public Health* (Bangkok). 2018;40(suppl 1):i39–49. <https://doi.org/10.1093/pubmed/fox149>.
19. Doole F, Littin S, Myers S, Somasekhar G, Steyaert J, Lansley K. Experiential learning for training future science policy and diplomacy experts. *JSPG*. 2022. <https://doi.org/10.38126/jspg210103>.
20. Geiger I, Bischoff L, Vogler T. Multiple parties behind and across the table: a role-play simulation of parallel, competitive order negotiations for training B2B sales professionals. *Ind Mark Manag*. 2022;103:170–82. <https://doi.org/10.1016/j.indmarman.2022.03.014>.
21. Vázquez-Vilchez M, Garrido-Rosales D, Pérez-Fernández B, Fernández-Oliveras A. Using a cooperative educational game to promote pro-environmental engagement in future teachers. *Educ Sci* (Basel). 2021. <https://doi.org/10.3390/educsci11110691>.
22. Tsai JC, Liu SY, Chang CY, Chen SY. Using a board game to teach about sustainable development. *Sustainability* (Switzerland). 2021. <https://doi.org/10.3390/su13094942>.
23. Chappin EJJ, Bijvoet X, Oei A. Teaching sustainability to a broad audience through an entertainment game—the effect of Catan: Oil Springs. *J Clean Prod*. 2017;156:556–68. <https://doi.org/10.1016/j.jclepro.2017.04.069>.
24. Gyetvai L, Vince Lovas B, Kiss M, Talas M, Halmosi B, Ara J, et al. Development of a negotiation-based serious game in virtual reality to help teach responsible consumption and production.
25. Geissler B, Steiner G, Mew MC. Clearing the fog on phosphate rock data—uncertainties, fuzziness, and misunderstandings. *Sci Total Environ*. 2018;642:250–63. <https://doi.org/10.1016/j.scitotenv.2018.05.381>.
26. Rittel HWJ, Webber MM. Dilemmas in a general theory of planning\*. *Policy Sci*. 1973. <https://doi.org/10.1007/BF01405730>.
27. Eckstein J, Bartanen M. British parliamentary debate and the twenty-first-century student. *Commun Stud*. 2015;66(4):458–73. <https://doi.org/10.1080/10510974.2015.1056916>.
28. Ponce P, Meier A, Méndez JI, Pepper T, Molina A, Mata O. Tailored gamification and serious game framework based on fuzzy logic for saving energy in connected thermostats. *J Clean Prod*. 2020. <https://doi.org/10.1016/j.jclepro.2020.121167>.
29. Bilgin CU, Baek Y, Park H. How debriefing strategies can improve student motivation and self-efficacy in game-based learning. *J Educ Comput Res*. 2015;53(2):155–82. <https://doi.org/10.1177/0735633115598496>.
30. Naeini J. Self-assessment and the impact on language skills [Internet]. *Educ Res*. 2011.
31. Kiernan D. Natural resources biometrics. Milne: OpenSUNYTextbooks; 2014.
32. Hedges LV. Distribution theory for Glass's estimator of effect size and related estimators. *J Educ Stat*. 1981;6(2):107–28. <https://doi.org/10.2307/1164588>.

33. Charlier N, Zupancic N, Fieuw S, Denhaerynck K, Zaman B, Moons P. Serious games for improving knowledge and self-management in young people with chronic conditions: a systematic review and meta-analysis. *J Am Med Inform Assoc.* 2016;23(1):230–9. <https://doi.org/10.1093/jamia/ocv100>.
34. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol.* 2013. <https://doi.org/10.3389/fpsyg.2013.00863>.
35. Yan Z, Wang X, Boud D, Lao H. The effect of self-assessment on academic performance and the role of explicitness: a meta-analysis. *Assess Eval High Educ.* 2023;48(1):1–15. <https://doi.org/10.1080/02602938.2021.2012644>.
36. Cohen J. *Statistical power analysis for the behavioral sciences.* London: Routledge; 1977.
37. Ellis PD. *The essential guide to effect sizes: statistical power, meta-analysis, and the interpretation of research results.* Cambridge: Cambridge University Press; 2010. (10.1017/CBO9780511761676).
38. McLaughlin MJ, Smolders E, Zhao FJ, Grant C, Montalvo D. Chapter one—managing cadmium in agricultural systems. In: Sparks DL, editor. *Advances in Agronomy.* Academic Press; 2021. p. 1–129 (10.1016/bs.agron.2020.10.004).
39. Haneklaus NH. Unconventional uranium resources from phosphates. *Encycl Nuclear Energy.* 2021. <https://doi.org/10.1016/b978-0-12-819725-7.00152-5>.
40. Chen M, Graedel TE. The potential for mining trace elements from phosphate rock. *J Clean Prod.* 2015;91:337–46. <https://doi.org/10.1016/j.jclepro.2014.12.042>.
41. Gaustad G, Williams E, Leader A. Rare earth metals from secondary sources: Review of potential supply from waste and byproducts. *Resour Conserv Recycl.* 2021;167:105213. <https://doi.org/10.1016/j.resconrec.2020.105213>.
42. Wu S, Wang L, Zhao L, Zhang P, El-Shall H, Moudgil B, et al. Recovery of rare earth elements from phosphate rock by hydrometallurgical processes—a critical review. *Chem Eng J.* 2018;335:774–800. <https://doi.org/10.1016/j.cej.2017.10.143>.
43. Cooper J, Lombardi R, Boardman D, Carliell-Marquet C. The future distribution and production of global phosphate rock reserves. *Resour Conserv Recycl.* 2011;57:78–86. <https://doi.org/10.1016/j.resconrec.2011.09.009>.
44. Qamouche K, Chetaine A, El Yahyaoui A, Moussaif A, Fröhlich P, Bertau M, et al. Uranium and other heavy metal sorption from Moroccan phosphoric acid with argan nutshell sawdust. *Miner Eng.* 2021. <https://doi.org/10.1016/j.mineng.2021.107085>.
45. Bilal E, Bellefqih H, Bourgier V, Mazouz H, Dumitras DG, Bard F, et al. Phosphogypsum circular economy considerations: a critical review from more than 65 storage sites worldwide. *J Clean Prod.* 2023. <https://doi.org/10.1016/j.jclepro.2023.137561>.
46. Hakkar M, Ezzahra Arhouni F, Mahrou A, Bilal E, Bertau M, Roy A, et al. Enhancing rare earth element transfer from phosphate rock to phosphoric acid using an inexpensive fly ash additive. *Miner Eng.* 2021. <https://doi.org/10.1016/j.mineng.2021.107166>.
47. Zhang P. Comprehensive recovery and sustainable development of phosphate resources. *Procedia Eng.* 2014;83:37–51. <https://doi.org/10.1016/j.proeng.2014.09.010>.
48. Steiner G, Geissler B, Haneklaus N. Making uranium recovery from phosphates great again? *Environ Sci Technol Am Chem Soc.* 2020. <https://doi.org/10.1021/acs.est.9b07859>.
49. Kim H, Eggert RG, Carlsen BW, Dixon BW. Potential uranium supply from phosphoric acid: a U.S. analysis comparing solvent extraction and ion exchange recovery. *Resour Policy.* 2016;49:222–31. <https://doi.org/10.1016/j.resourpol.2016.06.004>.
50. Shang D, Geissler B, Mew M, Satalkina L, Zenk L, Tulsidas H, et al. Unconventional uranium in China's phosphate rock: review and outlook. *Renew Sustain Energy Rev.* 2021. <https://doi.org/10.1016/j.rser.2021.110740>.
51. Tulsidas H, Gabriel S, Kiegiel K, Haneklaus N. Uranium resources in EU phosphate rock imports. *Resour Policy.* 2019;61:151–6. <https://doi.org/10.1016/j.resourpol.2019.02.012>.
52. López L, Castro LN, Scasso RA, Grancea L, Tulsidas H, Haneklaus N. Uranium supply potential from phosphate rocks for Argentina's nuclear power fleet. *Resour Policy.* 2019;62:397–404. <https://doi.org/10.1016/j.resourpol.2019.04.008>.
53. Diwa RR, Ramirez JD, Haneklaus NH. Uranium supply potential from imported phosphate rocks for the Philippine nuclear power program. *Extract Indus Soc.* 2023. <https://doi.org/10.1016/j.exis.2023.101303>.
54. Ud-Din Khan S, Ahmad A, Khan R, Haneklaus N. Uranium resources associated with phosphoric acid production and water desalination in Saudi Arabia. *Front Earth Sci (Lausanne).* 2024. <https://doi.org/10.3389/feart.2024.1341059>.
55. Haneklaus N, Sun Y, Bol R, Lottermoser B, Schnug E. To extract, or not to extract uranium from phosphate rock, that is the question. *Environ Sci Technol.* 2017;51(2):753–4. <https://doi.org/10.1021/acs.est.6b05506>.
56. Ye Y, Al-Khaleidi N, Barker L, Darwish MS, El Naggar AMA, El-Yahyaoui A, et al. Uranium resources in China's phosphate rocks - Identifying low-hanging fruits. *IOP Conf Ser Earth Environ Sci.* 2019. <https://doi.org/10.1088/1755-1315/227/5/052033>.
57. Scholz RW, Wellmer F-W. Although there is no physical short-term scarcity of phosphorus, its resource efficiency should be improved. *J Ind Ecol.* 2019;23(2):313–8. <https://doi.org/10.1111/jiec.12750>.
58. Mwalongo DA, Haneklaus NH, Lisuma JB, Mpumi N, Amasi AI, Mwimanzi JM, et al. Uranium dissemination with phosphate fertilizers globally: a systematic review with focus on East Africa. *Sustainability.* 2024. <https://doi.org/10.3390/su16041496>.
59. Haneklaus NH, Mwalongo DA, Lisuma JB, Amasi AI, Mwimanzi J, Bituh T, et al. Rare earth elements and uranium in Minjingu phosphate fertilizer products: Plant food for thought. *Resour Conserv Recycl.* 2024. <https://doi.org/10.1016/j.resconrec.2024.107694>.
60. Mwalongo DA, Haneklaus NH, Carvalho FP, Lisuma JB, Kivevele TT, Mtei KM. Influence of phosphate fertilizers on the radioactivity of agricultural soils and tobacco plants in Kenya, Tanzania, and Uganda. *Environ Sci Pollut Res.* 2023;30(34):83004–23. <https://doi.org/10.1007/s11356-023-27543-8>.
61. Mwalongo DA, Haneklaus NH, Lisuma JB, Kivevele TT, Mtei KM. Uranium in phosphate rocks and mineral fertilizers applied to agricultural soils in East Africa. *Environ Sci Pollut Res.* 2023;30(12):33898–906. <https://doi.org/10.1007/s11356-022-24574-5>.
62. Haneklaus N, Bayok A, Fedchenko V. Phosphate rocks and nuclear proliferation. *Sci Glob Secur.* 2017;25(3):143–58. <https://doi.org/10.1080/08929882.2017.1394061>.
63. Bevins JE, Laderman S, Goldblum BL, Katzenson E, Kendrick J, Krentz-Wee R, et al. A framework for assessing alternate proliferation pathways in the age of non-state actors. *Nonproliferation Rev.* 2018;25(1–2):87–110. <https://doi.org/10.1080/10736700.2018.1493172>.
64. Kelley R, Fedchenko V. Phosphate fertilizers as a proliferation-relevant source of uranium. *EUNon-proliferationPaper.* 2017;59.
65. Schnug E, Lottermoser BG. Fertilizer-derived uranium and its threat to human health. *Environ Sci Technol.* 2013;47(6):2433–4. <https://doi.org/10.1021/es4002357>.

66. Takeda A, Tsukada H, Takaku Y, Hisamatsu S, Nanzyo M. Accumulation of uranium derived from long-term fertilizer applications in a cultivated Andisol. *Sci Total Environ.* 2006;367(2):924–31. <https://doi.org/10.1016/j.scitotenv.2006.01.006>.
67. Sun Y, Wu B, Amelung W, Christensen BT, Pätzold S, Bauke SL, et al. Non-critical uranium accumulation in soils of German and Danish long-term fertilizer experiments. *Geoderma.* 2020;370:114336. <https://doi.org/10.1016/j.geoderma.2020.114336>.
68. Sun Y, Amelung W, Gudmundsson T, Wu B, Bol R. Critical accumulation of fertilizer-derived uranium in Icelandic grassland Andosol. *Environ Sci Eur.* 2020;32(1):92. <https://doi.org/10.1186/s12302-020-00367-w>.
69. Mathivanan M, Sabarathinam C, Mohan Viswanathan P, Senapathi V, Nadesan D, Indrani GG, et al. Mobilization and health risk assessment of fertilizer induced uranium in coastal groundwater. *Environ Res.* 2022;203:111791. <https://doi.org/10.1016/j.envres.2021.111791>.
70. Liesch T, Hinrichsen S, Goldscheider N. Uranium in groundwater—fertilizers versus geogenic sources. *Sci Total Environ.* 2015;536:981–95. <https://doi.org/10.1016/j.scitotenv.2015.05.133>.
71. Bigalke M, Ulrich A, Rehmus A, Keller A. Accumulation of cadmium and uranium in arable soils in Switzerland. *Environ Pollut.* 2017;221:85–93. <https://doi.org/10.1016/j.envpol.2016.11.035>.
72. Chen L, Liu J, Zhang W, Zhou J, Luo D, Li Z. Uranium (U) source, speciation, uptake, toxicity and bioremediation strategies in soil-plant system: a review. *J Hazard Mater.* 2021;413:125319. <https://doi.org/10.1016/j.jhazmat.2021.125319>.
73. Yamaguchi N, Kawasaki A, Iiyama I. Distribution of uranium in soil components of agricultural fields after long-term application of phosphate fertilizers. *Sci Total Environ.* 2009;407(4):1383–90. <https://doi.org/10.1016/j.scitotenv.2008.10.011>.
74. Singh S, Malhotra R, Bajwa BS. Uranium uptake studies in some plants. *Radiat Measure.* 2005;40(2):666–9. <https://doi.org/10.1016/j.radmeas.2005.01.013>.
75. Kratz S, Schick J, Schnug E. Trace elements in rock phosphates and P containing mineral and organo-mineral fertilizers sold in Germany. *Sci Total Environ.* 2016;542:1013–9. <https://doi.org/10.1016/j.scitotenv.2015.08.046>.
76. Verbeeck M, Salaets P, Smolders E. Trace element concentrations in mineral phosphate fertilizers used in Europe: a balanced survey. *Sci Total Environ.* 2020;712:136419. <https://doi.org/10.1016/j.scitotenv.2019.136419>.
77. European Parliament. Parliamentary question - E-002175/2013(ASW). 2013.
78. Spaiser V, Ranganathan S, Swain RB, Sumpter DJT. The sustainable development oxymoron: quantifying and modelling the incompatibility of sustainable development goals. *Int J Sust Dev World.* 2017;24(6):457–70. <https://doi.org/10.1080/13504509.2016.1235624>.
79. Eisenmenger N, Pichler M, Krenmayr N, Noll D, Plank B, Schalmann E, et al. The Sustainable Development Goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. *Sustain Sci.* 2020;15(4):1101–10. <https://doi.org/10.1007/s11625-020-00813-x>.
80. Wong R, van der Heijden J. Avoidance of conflicts and trade-offs: a challenge for the policy integration of the United Nations Sustainable Development Goals. *Sustain Dev.* 2019;27(5):838–45. <https://doi.org/10.1002/sd.1944>.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Terms and Conditions

Springer Nature journal content, brought to you courtesy of Springer Nature Customer Service Center GmbH (“Springer Nature”).

Springer Nature supports a reasonable amount of sharing of research papers by authors, subscribers and authorised users (“Users”), for small-scale personal, non-commercial use provided that all copyright, trade and service marks and other proprietary notices are maintained. By accessing, sharing, receiving or otherwise using the Springer Nature journal content you agree to these terms of use (“Terms”). For these purposes, Springer Nature considers academic use (by researchers and students) to be non-commercial.

These Terms are supplementary and will apply in addition to any applicable website terms and conditions, a relevant site licence or a personal subscription. These Terms will prevail over any conflict or ambiguity with regards to the relevant terms, a site licence or a personal subscription (to the extent of the conflict or ambiguity only). For Creative Commons-licensed articles, the terms of the Creative Commons license used will apply.

We collect and use personal data to provide access to the Springer Nature journal content. We may also use these personal data internally within ResearchGate and Springer Nature and as agreed share it, in an anonymised way, for purposes of tracking, analysis and reporting. We will not otherwise disclose your personal data outside the ResearchGate or the Springer Nature group of companies unless we have your permission as detailed in the Privacy Policy.

While Users may use the Springer Nature journal content for small scale, personal non-commercial use, it is important to note that Users may not:

1. use such content for the purpose of providing other users with access on a regular or large scale basis or as a means to circumvent access control;
2. use such content where to do so would be considered a criminal or statutory offence in any jurisdiction, or gives rise to civil liability, or is otherwise unlawful;
3. falsely or misleadingly imply or suggest endorsement, approval, sponsorship, or association unless explicitly agreed to by Springer Nature in writing;
4. use bots or other automated methods to access the content or redirect messages
5. override any security feature or exclusionary protocol; or
6. share the content in order to create substitute for Springer Nature products or services or a systematic database of Springer Nature journal content.

In line with the restriction against commercial use, Springer Nature does not permit the creation of a product or service that creates revenue, royalties, rent or income from our content or its inclusion as part of a paid for service or for other commercial gain. Springer Nature journal content cannot be used for inter-library loans and librarians may not upload Springer Nature journal content on a large scale into their, or any other, institutional repository.

These terms of use are reviewed regularly and may be amended at any time. Springer Nature is not obligated to publish any information or content on this website and may remove it or features or functionality at our sole discretion, at any time with or without notice. Springer Nature may revoke this licence to you at any time and remove access to any copies of the Springer Nature journal content which have been saved.

To the fullest extent permitted by law, Springer Nature makes no warranties, representations or guarantees to Users, either express or implied with respect to the Springer nature journal content and all parties disclaim and waive any implied warranties or warranties imposed by law, including merchantability or fitness for any particular purpose.

Please note that these rights do not automatically extend to content, data or other material published by Springer Nature that may be licensed from third parties.

If you would like to use or distribute our Springer Nature journal content to a wider audience or on a regular basis or in any other manner not expressly permitted by these Terms, please contact Springer Nature at

[onlineservice@springernature.com](mailto:onlineservice@springernature.com)