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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

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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].

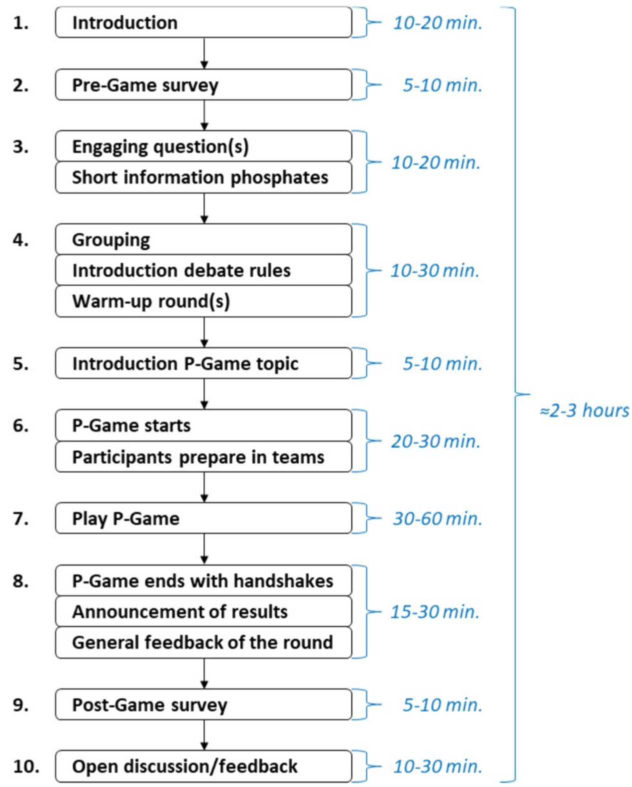

Fig. 1 Overview on how the P-Game was played

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

Post P-Game Survey

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

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

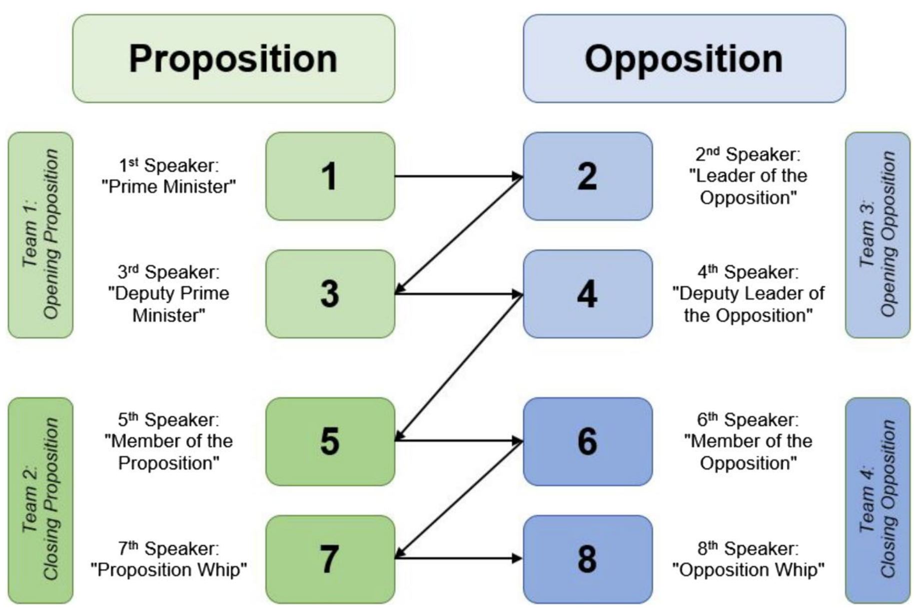

Fig. 3 Overview of British Parliamentary Style (BPS) Debating that provided a blueprint for the P-Game

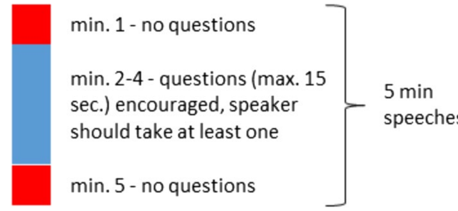

Fig. 4 Length of the speeches during the P-Game

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

Proposition for uranium recovery from phosphates		**Opposition** against uranium recovery from phosphates
- Distribution of radiotoxic uranium with fertilizers can largely be mitigated - Recovered uranium could be used as a nuclear reactor fuel and reduce commercial uranium mining elsewhere		- Uranium recovery is presently not profitable due to the low uranium prices and can thus result in increased prices for fertilizers - Recovered uranium could be a nuclear proliferation risk

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)".

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

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

With n_i the size of the sample i, $\overline{y_i}$ the mean of the sample i, and Γ the gamma function.

The function $J(n_1 + n_2 - 2)$ acts to unbias 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[1] 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[2] 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

[1] 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.

[2] 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.

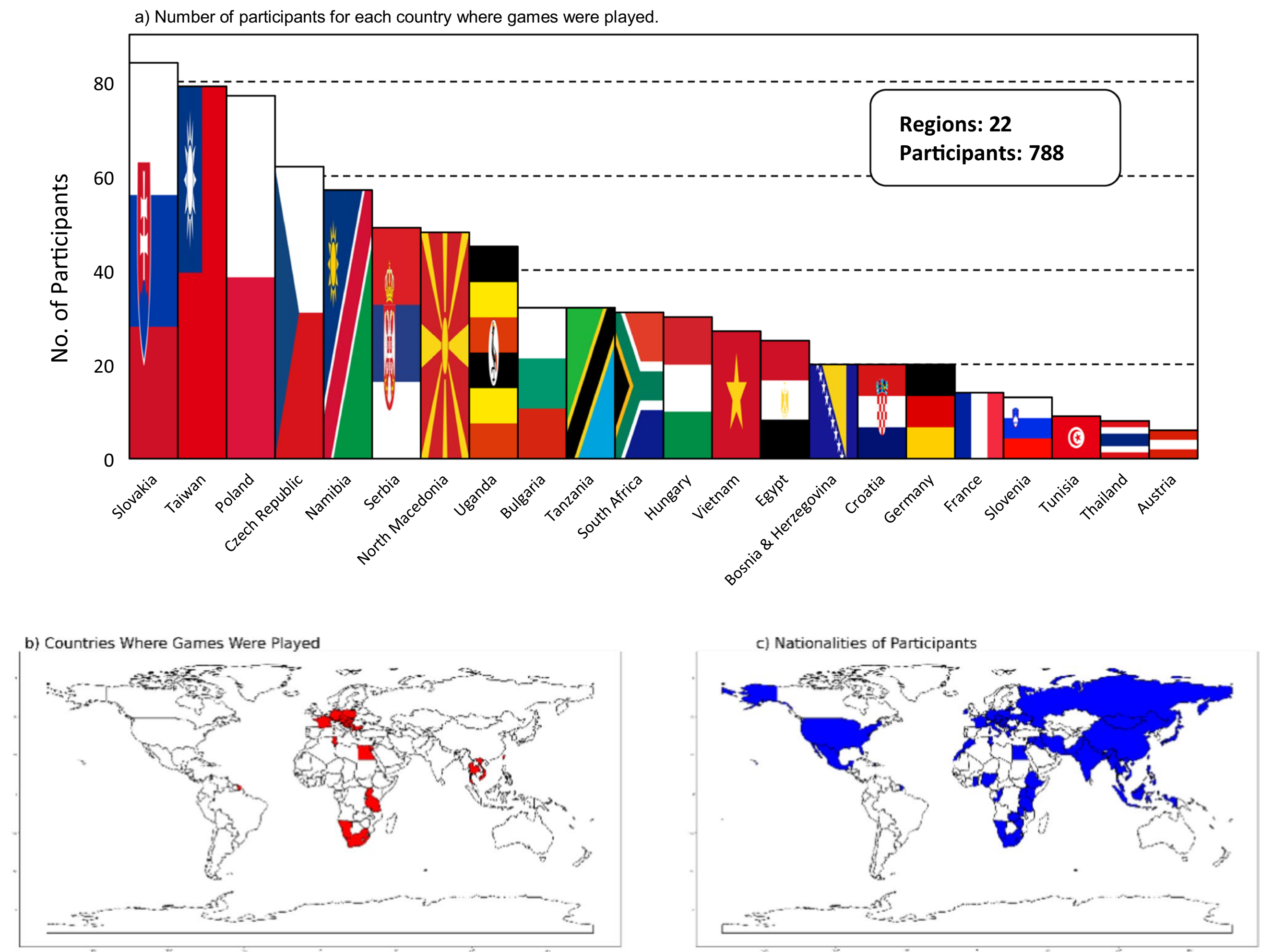

Fig. 6 **a** Number of participants in the games as well as countries where the game was played, **b** Geographic distribution of countries where games were played, **c** Geographic distribution nationalities of participants

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/pracitce 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 ± 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 (%)
Educational background		
Science students	480	60.9
Social science students	308	39.1
Education level		
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
Age		
< 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
Gender		
Male	363	46.1
Female	424	53.8

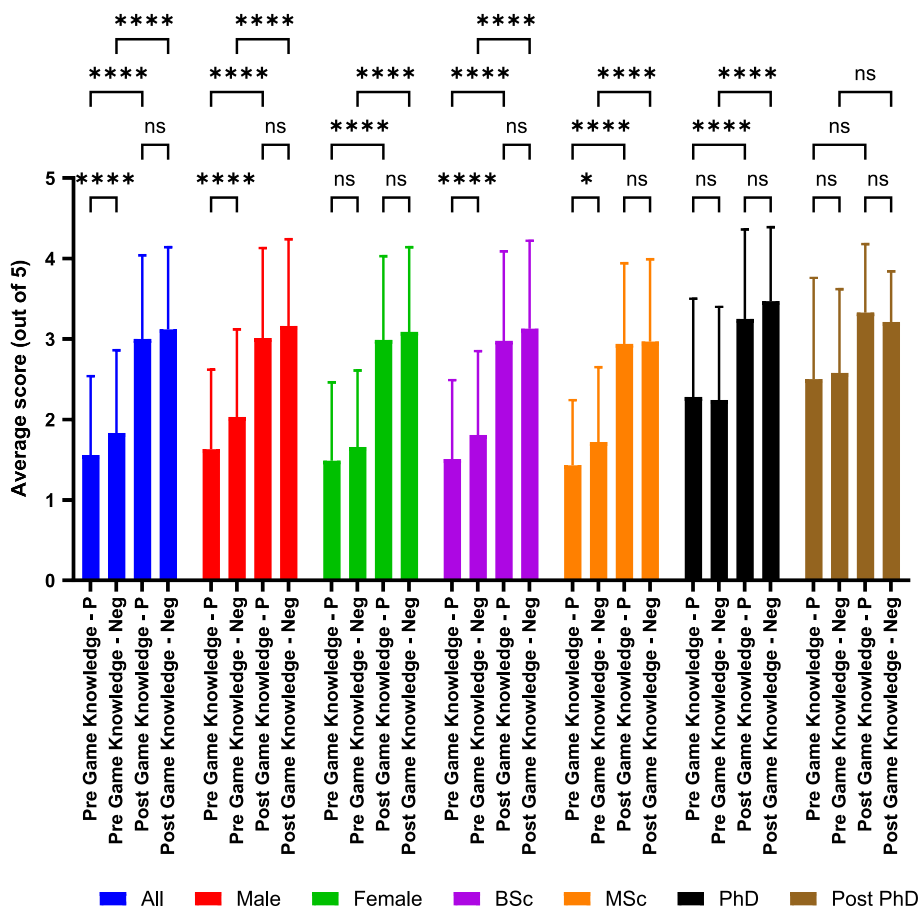

Fig. 7 The reported average self-assessment scores for the pre- and post-game surveys with the standard deviation shown as error bars. The significance of the differences between Pre- and Post-game averages as well as the knowledge areas for the different groups were quantified by two-way ANOVA comparisons 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)
All (n = 788)				
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		
Male (n = 359)				
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		
Female (n = 420)				
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		
BSc-Students (n = 490)				
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		
MSc-Students (n = 209)				
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		
PhD-Students (n = 50)				
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		
PhD Awarded (n = 12)				
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.

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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 Misihairabgwi: 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 Guzsvinecz: Formal Analysis, Investigation, Writing—Review & Editing, László Horváth: Formal Analysis, Investigation, Writing—Review & Editing, Sasho Josimovski: Formal Analysis, Investigation, Writing—Review & Editing, Martin Kiselicki: 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 Trenevska-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 Wacławek: 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.

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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.

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