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Teaching plant biology through “Plant senses”—a more engaging, holistic approach and introduction

Jana Krtková

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Abstract Higher education offers unique ways to provide students with knowledge of plant biology, as well as an engaging lens through which plants may be seen and appreciated. The tremendous volume of knowledge sometimes calls for introducing a different conceptual view to students who aim to become involved in plant research and related fields. It requires stepping back to consider the plant as a whole organism, connected to other organisms within an ecosystem and as a complex living form with its own plant-specific senses. Inspired by several best-selling books in this field, I launched a Plant Senses course. When using the Plant Senses tool to teach plant biology it is challenging to prevent students from over-interpreting and projecting animal features onto the plants, yet avoid an elitist zoocentric position that denies plant capacities we cannot observe with our animal perception. My course attempts to stimulate students to see the ecological importance of plants for much of life on this planet and to draw their attention to the economic value of plants to human societies. Here, I present the structure of the course and the topics covered. Further, I discuss the potential to spread this approach to other curricula and how these different fields may benefit from implementing such a course.

Keywords Senses · Teaching · Higher education · Plant cell biology · Plant physiology

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J. Krtková (✉)
Department of Experimental Plant Biology, Faculty of Science, Charles University, Prague, Czech Republic
e-mail: akcni.krtecek@post.cz

1 Why is teaching about plant senses important?

In recent decades plant science has witnessed tremendous progress and ever-deeper insight into both specific details and the complexity of plant life (Marks et al. 2021; Larson et al. 2023). Passing down this bounty of knowledge to students in higher education may become overwhelming for both students and teachers (OECD 2020). In such a situation and to prevent overloading or even a potential burnout of both sides, teachers may do well to reflect on the basic question: Is the student’s original motivation to study plant biology the desire to understand plant life—a living organism whose biology is so distinct from our own (Weber 2016; Pany et al. 2022)? If the answer is yes, then to fully study the biology of such living forms surely requires learning fascinating details of plant cell and bodily functions (National Research Council 1992; Wynn et al. 2017; Södervik et al. 2021; Cliff 2023). But even more, such undertaking requires a more complex, holistic approach to plant organisms and their interactions with their environment (Beyschlag and Ryel 2007; Uno 2009; Sheth and Taker

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2014; Weber 2016). Certainly, new detailed findings in plant biology may help sensitize students for seeing the organism in an extended context. However, students firstly need to see the plant organism within the bigger picture, starting from their initial motivation to study plant life in the first place—the awe and personal attraction to plant living forms (Wilson 1984; Wandersee and Schussler 2001; Louv 2008; Weber 2016; Jose et al. 2019). These aspects of the motivation to study plant biology are rooted in something ineffable that was so poetically called the biophilia hypothesis by E. O. Wilson—"the [to the some degree innate] urge to affiliate with other forms of life" (Wilson 1984). As humans, we can more easily relate to the motivations driving animal physiology. There is a tendency to ascribe human feelings and traits to other organisms including plants (see for example Calvo 2023). Despite this possibly unhelpful inclination toward anthropomorphism, its value for helping students become attuned to plants still should be explained to and developed for them (Louv 2008; Achurra 2022; Calvo 2023). The tendency still provides a starting point to begin understanding and exploring complex responses and processes in organisms that differ so dramatically (Bezanilla 2013; Jose et al. 2019; Achurra 2022; Cliff 2023).

Educators must contest the viewpoint that plants are "uninteresting" or "unimportant" (Pany et al. 2019). As sessile organisms, the plant response to threats or alterations in resource availability is often seen as less dramatic or less interesting—there are no rapid muscle movements, no fight-or-flight responses (Wandersee and Shussler 1999; Wandersee and Schussler 2001; Kubiatko et al. 2021; Achurra 2022). Consequently, there is a palpable reduction in the energy of the lecture hall and student attendance and participation in the lecture portion is often reduced (Wandersee and Schussler 2001; Fidanza 2006; Senchina 2008; Kováčik and Vydra 2023) and there is also a decline in the number of students pursuing degrees in plant science (Drea 2011; Jose et al. 2019; Stroud et al. 2022). Rather than focus on the time and resource investment that is required in plants to respond to environmental stimuli, a more effective approach is to highlight the immense capacity that plants have to absorb information from their environment in a daily context while staying in one place (Hershey 1992; Strgar 2007; Mazzolai et al. 2014; Kletečki et al. 2023). Like animals, plants have the ability to perceive light, mechanical, gravity and other stimuli—a fact that can be easily understood and appreciated by any student of biology if plants are given the time to be observed (Pany et al. 2019; Jose et al. 2019; Kubiatko et al. 2021). The lack of rapid movements in plants resulting in reduced attention can be further overcome by following plant movements using the Plant Tracer application for smartphones (Brenner 2017; Guercio et al. 2019).

The attempt to see the outer world "as a plant" may stimulate students to reestablish their connection with nature and to have a more direct experience in nature (Louv 2008; Uno 2009). Implementing a plant senses course in higher education may be of great potential to further develop ecological literacy and thus impact citizen science (Findler et al. 2019; Martin et al. 2020; Žalėnienė and Pereira 2021; Wang et al. 2022). Students can become future advocates for nature as well as plant research. By teaching plant biology through plant senses, an approach that takes into account solid science about molecular details of plant physiology and cell biology yet also pushes for a holistic approach to the plant organisms and their environment (Beyschlad and Ryel 2007; Uno 2009; Sheth and Taker 2014; Weber 2016), we may mitigate a problem that could be expressed by a simple metaphoric question: What does the loss of a plant species mean to a student who does not know the name of the species or the network of organisms that it interacts with (Louv 2008; Stroud et al. 2022)?

This idea of changing how we think about the context in which plant biology plays out and the possible role of plants as more active rather than passive participants in their environment lead to the development of a course called Plant Senses, inspired by sources such as the international besteller *What a Plant Knows* by Daniel Chamovitz (Chamovitz 2017) as well as further literature in this field and a discussion seminar taught at the University of Washington, Seattle, USA, by Elizabeth Van Volkenburgh. In this novel Plant Senses course, through the prism of plant distinct sensual capacities, students can simultaneously and in an accessible way be introduced to the complex processes of plant cell biology, signaling, growth and development, plant physiology and underlying molecular mechanisms (Chamovitz 2017).

While considering what a plant living organism senses from its environment, how it turns these stimuli into information and how it responds, students need to see plants in a proactive light and switch from the traditional anthropo and zoocentric perspective to a plant one (see for example Chamovitz 2017; Mancuso 2018; Calvo 2023). This idea is far from new. It was proposed by several leading scientists in this field, such as Daniel Chamovitz, Stefano Mancuso, František Baluška, Elizabeth Van Volkenburgh, Paco Calvo and others. Further, teaching plant biology through plant senses disrupts student's mechanistic view derived from platonic dualism, through which the organisms are looked at as a machine, as an object to dissect (Weber 2016), which puts aside the initial awe experienced while facing plant life. Importantly, in this course no supersensory or emotional approach is a substitute for a mechanistic perspective. For example, students are encouraged to avoid using diminutives, anthropomorphic terms and atributing human capacities to plants. Instead, they need to focus on molecular mechanisms and the ecological context. Students absorb solid science; they study groundbreaking, often pioneering research and different frames of understanding a plant as a complex whole and as a significant part of an ecosystem.

This topic also naturally lends to a lesson format based on active learning, which was demonstrated to benefit students in general (Bonwell and Eison 1991; Freeman et al. 2014). There is an ongoing active debate on plant senses in both the public arena and in academia. This creates a kind of "flipped" relationship between the student and the instructor that goes beyond the "flipped classroom" idea. In this case, the teacher can ask more than tell, include occasional group problem-solving, use personal responses (Freeman et al. 2014), ask students to think about potential applications of the research at home, encourage them to provide answers on specific questions for plant science. The educator can offer and demonstrate the argument, but the students become more active in looking for evidence in the research about how plants receive and respond to information from their environment. If we give them time and space their own ideas, the students become the protagonists of their experience during the course (Bonwell and Eison 1991; Fidanza 2006; Beckmann et al. 2015; Pany et al. 2019).

In following sections, I introduce the structure of the course in detail, include the list of topics discussed and the objectives to be reached at the end of each class. Next, I propose implementing this approach to other curricula and discuss its positive effects.

2 Plant Senses course

This course is optional and has been offered for bachelor, master programme students as well as for Ph.D. candidates once a year during the last 2 years. The first year, after extensive advertising (fliers, social media, word of mouth, personal recommendation), 15 students were enrolled, whereas the second year only 8 students were enrolled. There are no prerequisite classes or exams required. Since it is taught at the Faculty of Science of Charles University, the main target group are students of biology programmes, however, it is open to students of other faculties and universities as well: agronomy, health sciences, food technology etc. It is not intended as a substitute for traditional plant physiology, it aims to trigger interest with selected topics. The outline of the Plant Senses course is based, among other resources, on the second revised and updated edition of *What a Plant Knows* by Daniel Chamovitz (2017), *The Revolutionary Genius of Plants* by Stefano Mancuso (2018) and plant physiology textbooks [e. g. *Plant Physiology and Development* by Taiz and Zeiger (2014), plus further Czech textbooks]. A substantial part of the course is dedicated to recent scientific literature that appeared after the last editions of these books were published. Furthermore, new technologies developed for applied plant science are discussed. The literature allows for a view on a habitat from the plant´s perspective, where light, chemical, sound, mechanical, and proprioceptive stimuli from the plant environment, and plant respective responses are discussed. This approach "to see the world as a plant", however, requires a short comparison with the stimuli perception, signal transduction and cellular or physiological responses in animals and/or humans. A balanced approach requires students to be warned against pseudoscience and to be shown specific examples of such misguided work that was not reproducible and was lacking proper controls, such as Retallack's experiments on plant growth during exposure to classical or rock music or supposed beneficial effects of prayer on plants (Hershey 1992; Chamovitz 2017). Student's attention is also constantly drawn to potential controversies arising from over-interpreting results and from zoomorphism fallacies.

2.1 Topics covered

Detailed content and learning objectives of each class are listed in Table 1. Shortly, I cover light as a source of energy for photosynthesis versus light as an information, light signaling, light stress and light stress adaptation. I include interesting regional aspects, for example high UV radiance combined with the large temperature range between day and night, and high humidity in the high-altitude *páramo* ecosystem in South America, and examples of adaptation in the genus *Espeletia*.

I explain the importance of the canopy as "natural air conditioning" and its physical mechanisms by asking questions such as, "Why do we feel cool in the woods?". I address the role of the canopy in changing light conditions of the habitat, phototropism and Darwin's experiments on phototropism.

I introduce students to photoperiodism and include experience-based examples of conventionally grown crops, plants and model organisms. We discuss complex environmental clues that impact the development of these plants at different altitudes, latitudes, light conditions and stress conditions.

Further topics covered include: volatile organic compounds (VOCs) and their ecological role, hormonal signaling during pathogen attacks, chemicals involved in plant parasitism, allelopathy, solid scientific evidence for plant responses to sounds versus pseudoscience, sounds emitted by plants, the role of selected genes in root development, gravitropism. I mention hydrotropism and its economic impact in different parts of the world.

Substantial time is dedicated to the historical background of agricultural revolutions and their impact on human civilization. I follow up with current trends in agricultural research and cutting-edge technology employed in CGIAR centers, the role of genebanks, and knowledge gained through drought stress testing. I present a case study of water management in Israel—showing drip irrigation, desalination, and the formulation of water use policy.

The list of topics further includes: the role of shoot endodermis in proprioception, secondary metabolites related to environmental clues, plant memory, plant associative learning, mechanosensing, the role of plant hormones in plant growth and development such as auxin in gravitropism a phototropism, salicylic acid and jasmonic acid in stress signaling, plant nutation, signaling cascades, Ca^{2+} signaling, Ca^{2+}-binding proteins, ion channels, and plant movements dependent opon cell turgor. To explain electrical signaling in plants, we demonstrate examples in living plants. I also include a short introduction to the history of nature conservation in the USA (e.g. John Muir's legacy, national parks in the USA, giant sequoia and redwood species and their specific ecology). Finally, I introduce technology and architecture inspired by plants (https://www.pnat/net) and plants in space research.

2.2 Testing and exams

To provide further training for the students that regularly attend the classes (more than 80%) I encourage them to create a short grant proposal based on a topic discussed during the semester where they need to present their deep understanding of the respective cellular and physiological processes. Further, students must meet strict requirements of the tentative proposal (limited number of characters, defined sections, detailed experimental design). This option, I believe, is ideal, because it shows the highest level of learning results—the students are able to compose elements of knowledge into a new whole, including a short introductory section reviewing what they have learned about the respective topic, summary of their sources, suggesting new hypotheses, defending their scientific ideas, suggesting experimental design, plus organizing the timing and experimental sequence as well as defining the outcomes of their proposal.

A second option (the only one for students with less than 80% attendance) is the classical exam where students demonstrate gained knowledge as well as deeper insight into the discussed topics. Specific questions showing the learning outcomes (https://www.celt.iastate.edu/instructional-strategies/preparing-to-teach/tips-on-writing-course-goalslearning-outcomes-and-measureable-learning-objectives/)—such as "describe the mechanism of…, compare…, draw…, assess…"—are requested.

Table 1 The title, content and learning objectives of each class

Title of the class	Content	Learning objectives
1. Why are plants important + what a plant "sees" I:	The importance of the canopy as "natural air conditioning" and its physical mechanisms. Visual spectra—plants versus humans. The role of the canopy in changing light conditions of the habitat. Phototropism and Darwin´s experiments on phototropism. Receptors—general structure, photoreceptors—humans versus plants. Discovery of photoreceptors in plants (mutant lines). Light-source of energy for photosynthesis versus information, light signaling, light stress and light stress adaptation. Specific regional aspects (high UV radiance combined with the large temperature range between day and night, and high humidity in the high-altitude *páramo* ecosystem in South America) and adaptation in the genus *Espeletia*.	Respond "Why do we feel cool in the woods?" and explain the underlying physical principle. Categorize visual spectra in plants and humans and analyze the changes of light conditions in the environment due to reflection, transmission and absorption in canopy. Analyze the result of Darwin´s experiment. Construct a representation of molecular photoreceptor and compare human and plant photoreceptors (wavelengths, localization, chromophores). Create a diagram that illustrates the light spectra used in photosynthesis vs as information and attribute specific pigments and photoreceptors to the respective wavelengths. Evaluate morphological adaptations to high radiance.
2. What a plant "sees" II:	Photoperiodism. Own experience-based examples of conventionally grown crops, plants and model organisms (lettuce, strawberries, radish, *Poinsettia*, *Arabidopsis*, tobacco…). Complex environmental clues that impact the development of these plants at different altitudes, latitudes, light conditions and stress conditions. Short-day vs. long-day plants (examples). Phytochrome (Pr vs. Pfr form). Cryptochrome. Molecular mechanism of photoperiodic induction of flowering. Unresolved case of *Boquila*.	Explain the concept of photoperiodism. Contrast long-day, short-day and neutral plants. Discuss further environmental stimuli that affect photoperiodism (altitude, drought stress, …). Draw a diagram of the conversion of phytochromes. Analyze the processes in plants where phytochromes and cryptochromes are involved.
3. What a plants "smells" I:	Human and animal olfactory capabilities. Olfactory signaling cascade in humans. Ethylene in plants. Receptors and functions of ethylene. Climacteric and non-climacteric fruits. Senescence. Volatile organic compounds (VOCs) and their ecological role. Hormonal signaling during pathogen attacks, chemicals involved in plant parasitism. Holoparasitic and hemiparasitic plants.	Draw ethylene signaling pathway. Describe processes where ethylene is involved. Contrast ripening processes in climacteric and non-climacteric fruits. Analyze structural and biochemical processes during senescence. Identify the categories of plant parasites and describe the development of parasite-host interaction.
4. What a plant "smells" II:	Methyl salicylate vs salicylic acid, methyl jasmonate versus jasmonic acid. The effect of salicylic acid on plant cytoskeleton. Plant pathogens. Plant pathogens applied in research (CaMV, *Agrobacterium tumefaciens*). Plant defense—mechanical barriers, secondary metabolites, inducible plant defense system.	Contrast the attack of insects and bacteria or virus. Categorize plant pathogens. Diagram the *Agrobacterium tumefaciens*-mediated plant transformation process. Analyze anatomical features that provide constitutive defense. Identify the categories of plant secondary metabolites.

Table 1 (continued)

Title of the class	Content	Learning objectives
5. What a plant "tastes" I:	Human biology of taste, receptors. Uptake and transport of minerals in roots. Macronutrients, micronutrients. Receptors. Water uptake. Aquaporins. Stomata. Transpiration. Hygroscopic movements in plants (seeds, ferns).	List macronutrients. Identify plant structures and molecules where these occur. Outline their role. Describe mineral and water uptake in roots. Draw a diagram of root anatomical structure. Describe the apoplastic barrier. Determine the role of suberin. Analyze the environmental conditions that affect transpiration. Assess the role of hygroscopic movements in nature.
6. What a plant "tastes" II:	Historical background of agricultural revolutions and their impact on human civilization. Current trends in agricultural research and cutting-edge technology employed in CGIAR centers, the role of genebanks, drought and heat stress testing. Biofortification (Fe, Zn). Case study—water management in Israel—drip irrigation, desalination, the formulation of water use policy. Split-root technique. Allelopathy (*Juglans regia*, *Robinia pseudoacacia*).	Compare the culture of a human population before and after agricultural revolutions. Describe the current problems in food sustainability and agriculture that human population is facing and how they are addressed. Diagram the split-root method. Describe allelopathy.
7. What a plant "feels" I:	Touch in humans. Tendrils and twining in plants. Touch-induced growth inhibition. *TCH* genes. Ca^{2+} signaling. Ca^{2+} and cytoskeleton.	Describe the known mechanisms of tendril curling. Analyze the effects of touching plants. Diagram the Ca^{2+} signaling pathway.
8. What a plant "feels" II:	*Dionaea muscipula*. Presentation of real carnivorous plants. Turgor pressure. Pulvinus cells in *Mimosa pudica* and their role. Electrical signaling. Ion channels—structure, localization, specificity, function.	Desribe the mechanism of closing the trap and electrical changes. Describe closing the leaves of the *Mimosa*. Categorize plant ion channels.
9. What a plant "hears":	Signaling pathways in auditory system in humans. History of the research of the role for sound in plants. Pseudoscience vs. solid science. Root phonotropism. Insects´ chewing vibration. Pollinating insects´ vibrations. Hydrotropism and its economic impact. Sounds emitted by plants—cavitation, sounds during drought stress.	Analyze the flaws in the first studies of the effect of sound on plants. Describe the experimental design and results of recent studies. Explain why and when cavitations occur.
10. How a plant knows where it is I:	Human proprioception—structures, signaling. Plant gravitropism (positive, negative). Root tip. Darwin, Němec, Friml and further research. The role of auxin in root gravitropism vs shoot phototropism. Auxin efflux transporters, PIN3 in root gravitropism. Nutation. Plant research in space (ISS). Parabolic flights. Technical innovations and architecture inspired by plants—plantoids, hygroscopic properties of *Erodium* seeds, jellyfish barge.	Contrast root and shoot gravitropism. Draw anatomic structures and diagram molecular mechanisms involved in these processes. Choose examples of plant research in space. Evaluate why technology can be inspired by plants.

Table 1 (continued)

Title of the class	Content	Learning objectives
11. How a plant knows where it is II + the necessity of direct contact with nature (Muir´s legacy and nature conservation):	Shoot endodermis. Plant movements, mutants of *Pharbitis nil* defective in circumnutation. The role of selected genes in root development (*SCARECROW, SHORT-ROOT, WEREWOLF*). John Muir´s legacy, national parks in the USA, giant sequoia and redwood species and their specific ecology.	Diagram shoot anatomy and highlight endodermis. Describe its role. Describe the reserch leading to its discovery. Analyze the role of *SCR* and *SHR* in root endodermis development. Desribe the effect of *werewolf* mutation.
12. What a plant "remembers":	Tulving´s 3 levels of memory. Plant memory. R. Dostál—"morphogenetic memory". Epigenetic memory and stress. Vernalization. Tendrils—M. Jaffes´s experiments, *Mimosa pudica*—recent experiments, *Dionaea muscipula*—electrical signaling and "memory". Plant associative learning.	Evaluate the concept of plant memory. Choose examples of plant procedural memory. Describe the fundamental principles of epigenetics and its implementation in vernalization and stress adaptation. Describe recent studies on plant memory. Contrast conditioned and unconditioned stimuli from the plant´s perspective.
13. Future prospects and students´ grant proposal presentations	Examples of unresolved issues, recent findings. Presentation of students´ grant proposals. Discussion.	Students analyze problems in experimental design. Suggest further experiments or improvements. Students present their grant proposals, show knowledge of the current state of research and discuss the experimental design suggested.

2.3 Obligatory and supplemental reading

A substantial component needed to pass the course is a student's home preparation. They will read, understand and interpret *What a Plant Knows* by Daniel Chamovitz (2017) and supplement gained information with recent original research papers. Students usually welcome further reading, e. g. *Brilliant Green* by Mancuso and Viola (2015), *The Revolutionary Genius of Plants* by Mancuso (2018), etc. In the future, an interesting update will be Paco Calvo´s *Planta Sapiens* (2023).

2.4 Outlook

To better address students´needs and stimulate their motivation I will implement the following measures into the course:

- A poll and analysis to track the demand for this type of course among students
- A self-report review providing feedback on how much knowledge the students think they gained by this approach compared to traditional plant biology classes followed by data analysis
- A poll and analysis to track comments and suggestions (class size, preferred topics, direct observation)
- A self-report review mapping interest in reconnecting with nature inspired by this course followed by data analysis
- More direct observation employing technology – for example following plant movements using the Plant Tracer smartphone application (Brenner 2017; Guercio et al. 2019)

3 Case study—is this teaching approach used in Czechia?

In order to answer the question of whether a similar Plant Senses teaching approach is prevalent in higher education, I focused on public universities and colleges in Czechia.

From publicly available systems containing lists of classes that are offered at all 26 Czech public colleges and universities, listed on the web page of the Czech Ministry of Education, Youth and Sports (https://www.msmt.cz/vzdelavani/vysoke-skolstvi/

prehled-vysokych-skol-v-cr-3?lang=1), a search retrieved only a single result of Plant Senses course at Faculty of Science, Charles University (my course; https://is.cuni.cz/studium/eng/predmety/index.php?do=predmet&kod=MB130P27). The search for classes at the University of South Bohemia in České Budějovice, which has a rich background in biology, revealed no results for a plant senses class (for courses, see https://wstag.jcu.cz/portal/studium/prohlizeni.html?pc_lang=en). An extended search of that school´s offerings retrieved tangential results only, in animal biology at its Faculty of Science: Ecology of Sensory Perception (in animals; https://wstag.jcu.cz/StagPortletsJSR168/ProhlizeniPrint?stateClass=cz.zcu.stag.portlets168.prohlizeni.predmet.PredmetSylabusState&predmetZkrPrac=KZO&predmetZkrPred=374&predmetRok=2023&predmetSemestr=LS&portalLocale=cs, see also Supplementary Information), Neurophysiology and Physiology of Senses (in animals; https://wstag.jcu.cz/StagPortletsJSR168/ProhlizeniPrint?stateClass=cz.zcu.stag.portlets168.prohlizeni.predmet.PredmetSylabusState&predmetZkrPrac=KZO&predmetZkrPred=671&predmetRok=2023&predmetSemestr=LS&portalLocale=cs, see also Supplementary Information). Intriguingly, among the universities screened, only a single comparable class in plants was found at Mendel University in Brno. There, an optional class on Plant Signaling Pathways for PhD students is offered (https://is.mendelu.cz/katalog/syllabus.pl?odkud=;zobrazit_sklad=0;zobrazit_obdobi=0;obdobi=;zpet=/katalog/index.pl?vzorek=rostlin,Dohledat=Dohledat,fakulta=43210,fakulta=43410,fakulta=43510,obdobi=446,obdobi=445,obdobi=444,jak=dle_jmena;predmet=148704;typ=81;jazyk=3;vystup=1, see also Supplementary Information).

Such a low number suggests further questions: Why is this type of class not offered? If this type of class would be offered as an option in the obligatory curriculum, would students preferentially choose this type of class compared to a traditional type of class? Are students interested in this type of course in the first place? If so, is it the majority or just a small number of students? Would students benefit from this class in their future curriculum or professional life? What is the situation in other countries with a rich plant biology teaching tradition? To answer these questions, further research is needed.

4 Future prospects: plant senses as a bridge to plants—potential implementation of the course in different curricula

The search of classes offered at 26 Czech public universities revealed several trends in higher education that would benefit from implementing this type of course. First, many universities and colleges are extending their study programs and establishing new biology or plant biology departments. Where there are any classes in plant biology offered at all, it is mostly plant physiology, plant ecophysiology or phylogeny (see, for example, the information systems at the Technical University in Liberec: https://stag.tul.cz/portal/studium/prohlizeni.html; University of West Bohemia in Plzeň: https://portal.zcu.cz/portal/studium/prohlizeni.html?pc_lang=en; Jan Evangelista Purkyně University in Ústí nad Labem https://portal.ujep.cz/portal/studium/prohlizeni.html?pc_lang=en). In those cases, a plant senses-oriented approach or supplementary course may offer an introduction into or a review of plant processes, as well as provide deeper insight or specific details.

Second, in many study programs that are not primarily plant oriented, but include courses in animal physiology, cell biology, or cell signaling, the intentionally unorthodox title “Plant Senses” may trigger curiosity and interest (Kubiatko et al. 2021; Achurra 2022; Hyland and Zou 2022). For many students, it can offer a point of entry to the plant world that they have often neglected, did not know of or even have never seen (Wandersee and Shussler 1999, 2001; Achurra 2022). The title is intended to draw attention and trigger strong reactions in people from different fields. By doing so, a Plant Senses course offers a wonderful platform from which to discuss the differences and continuities in animals, plants and other organisms—how do these different groups perceive stimuli from their environment, which signaling cascades are involved, which molecules and structures are involved in signal transduction, and how do these organisms respond to different stimuli on cell, organ and body level (Bezanilla 2013; Kubiatko et al. 2021; Cliff 2023). This equal exposure to different sensory worlds in animals and plants may counteract plant blindness (Jose et al. 2019; Pany et al. 2022) and enhance interest in plant biology.

Third, the universities and colleges offering classes focused on plant food production, fruits, vegetables and spices, plant secondary metabolites for medical use in both humans and animals, biotechnology, plant products or even technology and green urbanism may benefit from a Plant Senses course, because it has a great potential to integrate with these disciplines (Gutiérrez 2002; Louv 2008; Pany et al. 2019; Kletečki et al. 2023).

Experts in plant materials, plant inspired architects and specialists in technology and innovation would also benefit from gaining insight into, for instance, plant hydrotropism, plant hygroscopic movements, plant nutation, plant tropisms, etc. (Mazzolai et al. 2014; Wang et al. 2017; Steiner et al. 2017; Patel et al. 2023). Through its interdisciplinary approach, the Plant Senses course may channel students´ focus into unexpected fields, for example in technology and architecture (Mancuso 2018; https://www.pnat.net/), and these innovations may lead to plant science progress in the future.

Finally, understanding the complex interactions between plants and their environment, such as plant host-parasite interactions, volatile organic compounds (VOCs)-mediated interactions with other organisms, potential allelopathy between invasive and native species etc., is knowledge crucial for nature conservation professionals, environmentalists, environmental educators, urbanists, park and landscape designers (Beyschlag and Ryel 2007; Louv 2008; Silva et al. 2015; Adams and Savahl 2017; Wang et al. 2022; https://www.pnat.net/).

Without a doubt, education policies lead to improvements in social and environmental well-being. In 1977, the Intergovernmental Conference on Environmental Education in Tbilisi (today's Georgia), organized by the United Nations Education, Scientific, and Cultural Organization (UNESCO) in cooperation with the U.N. Environment Program (UNEP) Europe, called for promoting environmental education to all age groups and socio-professional groups in the population (Tbilisi Declaration 1978). Environmental education was adopted by many states (Scott and Oulton 1998). For instance, in 1978, Czechoslovakia ratified that declaration and the state eventually implemented mandatory environmental education at all levels (Jančaříková 2023; see for example Framework Educational Programme for Basic Education 2023). This wisdom of such an academic requirement supplemented with a plant senses approach can be a tool to directly reconnect students with nature, involve them in after-school activities and help to prevent ecophobia (Louv 2008; Adams and Savahl 2017).

5 Conclusion

Higher education may substantially affect students´ future careers, environmental attitudes and their behavior in society (Findler et al. 2019; Žalėnienė and Pereira 2021; Wang et al. 2022). At the same time, the awe and respect experienced in nature were reported in the early life of many biologists and often had a formative impact on their carreers (Louv 2008). Direct experience and time spent in nature have been demostrated to have a positive impact on physical and mental health, improved concentration and cognitive functions in humans (Taylor et al. 2002; Taylor and Kuo 2009; Adams and Savahl 2017; Martin et al. 2020) and was suggested as one of the formative stimuli necessary for the future stewardship of nature (Louv 2008; Adams and Savahl 2017; Martin et al. 2020). Therefore, biophilia and the awe experienced in higher education while learning about the way plants function, interact with their environment, plus employ different plant survival strategies, may contribute to a shift in values in students and to their future climate and Earth stewardship and engagement in sustainable practices (Adams and Savahl 2017; Wang et al. 2022). Teaching plant biology through plant senses, i.e. from the perspective of the very living organism that plant biology teaches about, may represent a unique and novel tool to revive student's initial awe they have experienced in nature during direct contact with plant and other living forms (Louv 2008; Pany et al. 2022). This approach to see the habitat "as a plant", i.e. from the plant´s perspective, seems to awaken students´ attention, curiosity, deeper interest and motivation to learn, evident from the way students frequently asked detailed questions and demanded further sources of information. The course set-up allows for an individual approach that may be manifested by personalized topics and supports the inclusion of students with special needs. The unorthodox concept stimulates debate compared to standard plant biology classes, and facilitates a shift away from passively listening to an instructor's lecture (Beckman et al. 2015).

Furthermore, the approach should provoke critical thinking (Brent and Felder 2014; https://teaching.cornell.edu/using-effective-questions)—students may actively consider the limits of current knowledge, suggest further experiments or a different experimental design. Finally, this approach goes beyond the frontier of biology—it integrates several disciplines and shows the need to put biological problems into innovative broader contexts that may include social economic studies, psychology, geography, technology, ethnography, cultural studies, linguistics, arts and other disciplines.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

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