ARTICLE

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See the world from a plant's perspective: on creating an interactive multimedia sculpture implying plant optics

Alexandra Burnusuz [1✉], Mariia Moshchenskaia[1], Veronika Prizova[1], Mikhail Shalepo[1], Maxim Rider[2], Viktor Zakharov[2], Ippolit Markelov[1], Mikhail Petrov[3] & Dmitrii Kadyrov[1]

Humans constantly interact with their environment, with other humans, as well as natural and artificial non-human agents. Nevertheless, our somatosensory system limits the diversity of our ways of communicating. Such organisms as plants thus escape our notice, blending into the landscape. This phenomenon is called *Plant blindness*. This leads not only to indifference and lack of empathy towards plants among ordinary people but also to a deficit in funding plant conservation. We believe that it is important to develop connections and also rethink the relationship between humans and flora. This paper examines the *Plant turn* in the context of an art-science project titled *Plantoverse*. The scientific part of the project is based on a study of plant epidermis cells, which possess optical properties and function as a "lens". The data acquired via confocal microscopy was used to construct a mathematical model of these lenses which in turn formed the basis of the artistic work. It is a representation of the plant epidermis in a digital environment. The work allows us to look at ourselves through "plant optics'' and find new tools for interacting with the vegetal world. This interdisciplinary approach can help transfer knowledge about flora from the professional environment to lay society and form a new, more empathetic view toward plants.

[1] BioArt Lab, Art & Science Center, Institute of International Development and Partnership, ITMO University, Saint Petersburg, Russia. [2] "Hybrid Nanostructures for Biomedicine" Laboratory, International Research and Educational Center for Physics and Technology of Nanostructures, ITMO University, Saint Petersburg, Russia. [3] Independent Researcher, Moscow, Russia. ✉email: alexandraburnusuz@gmail.com

Introduction

Plant blindness. Since humans are embedded in the world, the development of new methods of communication between humans and nonhumans is of significant relevance. However, the human somatosensory system limits the diversity of ways to communicate, which leads to the exclusion of some nonhumans from the active field of our attention. Although modern philosophy has become less anthropocentric, some organisms are still perceived as passive elements of the environment. Plants are among these organisms. The reasons for our indifference to them are complex and multifaceted, with the phenomenon itself labelled *plant blindness* (Hershey, 2002). Yet the term is not a mere stylistic device. For instance, even students in biology departments rarely choose to study plants, not to mention the ignorance of non-professionals (Balas and Momsen, 2014). Consequently, this leads to a prevalence of funding for animal — but not plant — conservation. (Jose, Wu and Kamoun, 2019). Thus, a funding disparity may eventually lead to ecosystem disparity. Are people really that unfair?

Comprehensive research by Wandersee and Schussler reveals that one of the reasons lies in our mechanisms of visual perception (Wandersee, Schussler, 1999). Although the plant community is usually the basis of particular biocenoses, such as rainforests, chaparrals, or steppes, plants are typically perceived as part of the landscape, while animals catch our attention more easily. This is partly related to plants' static and silent nature, though they are not actually motionless (Guerra et al., 2019). Besides, plant communities are usually monochrome, which also affects our perception (Wandersee, Schussler, 1999). Furthermore, our bodies' dissimilarity explains a lack of empathy for floral species and why people are more likely to sympathise with animals (mammals in particular) (Jose, Wu and Kamoun, 2019). For instance, as soon as some mammals exhibit "facial expressions" and vocalisation similar to human children, it triggers some neural and hormonal mechanisms of parental behaviour (Feldman, 2017), especially if these animals are furry and small. Thus, inattention in terms of somatosensory mechanisms and attitude is the basis of plant blindness.

The plant turn. To preserve plants and treat them more ethically, we should first expand our knowledge of the floral world. For example, the role of animals in human society, social sciences, and humanities has gradually changed, adapting to new cultural norms, traditions, and values. It began with comprehensive animal studies that contributed to an interest in animals. Afterward, it was reflected in the desire to understand "non-human agents" and launched the *Animal turn* (Waldau, 2013), an increase in researchers' attention towards the animal world (Wolfe, 2011). In other words, first comes awareness, then compassion. People have become not only more aware of animals but also more concerned about treating them ethically. The same process has just begun with plants. This is a result of new discoveries in plant biology, due to which plants are considered active agents of the environment (Khait, Lewin-Epstein et al., 2023) (Chamovitz, 2020). We believe that this knowledge should be shared with society in order to support the Plant turn, balancing out the trend towards the Animal turn.

The Plant turn as a subject of the sociocultural sphere was also interesting to observe during the COVID-19 pandemic (Burke, Sherwood et al., 2022). Forced to stay indoors, people felt the need to interact with the plant world. Those who found themselves outside cities embraced gardening and caring for plants. Under conditions where interacting with other humans was unsafe, people were forced to move away from the established anthropocentric ideas and activities and turn towards the plant world. We can observe a transformation in relation to plants: from employing plants to create a sense of cosiness in space and enhance human well-being, to the gradual recognition of subjectivity for plants (Josifovic, De Graaff et al., 2016). The idea of the urban jungle has been replaced by the Plant Parent (Burke, Sherwood et al., 2022). This phenomenon describes how people become interested in plants, follow their development, care for them, and thereby form an emotional connection. Tending to plants becomes not only an attempt to ease one's state of mind but also a popular trend. Plantfluencers share photos of their green wards on social media, emphasising the individuality of plants (Szczygielska and Cielemęcka, 2019). Simultaneously, the phenomenon of radical landscape urbanism, in other words, informal landscaping, or guerrilla gardening, is once again becoming popular. A striking example of this is *Villa Compostela*, which emerged at a composting site (Mikadze, 2020). This suggests an expression of people's desire to be surrounded by a community of plants. As we can see there is some turn towards plants, albeit still modest.

How can we reinforce an emerging scientific and emotional interest in plants? We hypothesise that it could be achieved by making people wonder to what extent the way plants communicate differs from ours and what our place in this communication is. We decided to look for data on the phenomenon of plant physiology that (i) would be relatively accessible to non-biologists and (ii) can engage the audience. How does it help to enhance empathy? For example, if people believe that plants do not feel physical impact, then they do not take into account the plant's potential reaction to this type of stimulus during an interaction. In other words, people will not put themselves in the plant's proverbial shoes and show empathy. This leads to the idea that we can help promote a conscious relationship with plants and accept their value. What if we put reasonable scientific data into a more imaginative and engaging form? This is how the concept of *Plantoverse* was born—a space where people can look at themselves through the optics of a plant organism and see themselves from the point of view of the other. *Plantoverse* is an interactive multimedia sculpture inspired by a hypothesis about the mechanism that links the light sensitivity of plant epidermal cells to leaf morphogenesis. In this concept, the epidermal cells of a leaf act as convex or plano-convex lenses. Presumably, it helps plants gain information via optic-based inputs regarding both illumination and surrounding objects (Guerra et al., 2019). Gottlieb Haberlandt was the first to propose this idea back in 1905, with it gaining further support from Charles Darwin and Harold Wager. In the first quarter of the 21st century, S. Mancuso further developed the plant "vision" hypothesis (Baluška and Mancuso, 2016). By interacting with the *Plantoverse* and trying out non-human optics, we are not only able to look at the other as a subject of its own life but to also reconsider the boundaries of relationships within a multispecies ecosystem. Our project merges the digital interpretation of the data from our research based on the aforementioned hypothesis with a physical embodiment of both scientific and artistic concepts. Using the Art & Science approach, we are able to employ the advantages and capabilities of both spheres, such as technical resources and methods of data representation. Thus, our Art & Science project *Plantoverse* presents a potential way of addressing the problem of communication between humans and nonhumans, a way of revealing the phenomenon of plant otherness. Since appreciation of contemporary artwork requires an understanding of the concept behind it, we would like to introduce our reader to (i) plant morphology and physiology that follow the laws of optics, (ii) mathematical modelling of these adaptations, (iii) our artistic approach to interpreting this data.
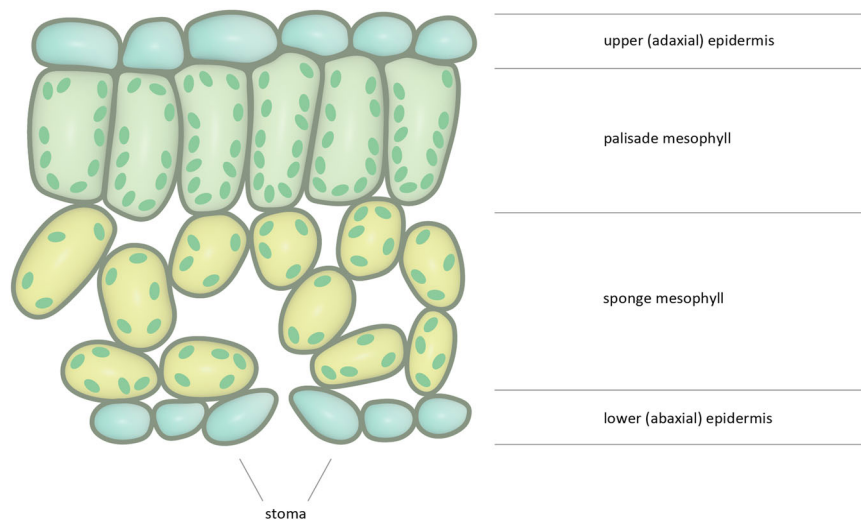
Fig. 1 Scheme for plant leaf cross-section. Mesophyll layer thickness ratio can vary across species. Original illustration.

Research on optical properties of plant cells, hypotheses proposed earlier. Above we have mentioned the dissimilarity between animal and plant morphogenetic strategies. Indeed, whereas most animals familiar to us (particularly, vertebrates) are unitary organisms, plants possess a modular organisation. Some of them are even fractal. In other words, plants consist of repeated fragments, organs, and parts. Moreover, these parts are relatively autonomous, which does not fit into our understanding of integrity and individuality. The plant leaf is one of these recurring organs and the main interface for interaction between the plant's above-ground part (the shoot) and the environment. Each plant leaf is covered by epidermis on both the upper (adaxial) and lower (abaxial) sides (see Fig. 1). This tissue consists of transparent cells without active chloroplasts, large vacuoles, and intercellular spaces (Poulson and Vogelmann, 1990). The main function of the epidermis is believed to be protection from excessive transpiration because of the cuticle and trichomes (leaf "hairs") (Robinson and Roeder, 2015). Among additional functions, one can mention protection from fungal infections (Wang et al., 2020) and solar over-irradiation (as in Mediterranean sclerophyll). Thus, the epidermis is usually called "protective" or "covering" tissue, and in the case of leaves, its function is considered rather auxiliary. This is because a leaf is mainly associated with photosynthesis, a process crucial for plant metabolism. This process occurs in the mesophyll. It is the tissue between the upper and lower epidermal layers. Mesophyll cells contain numerous active chloroplasts and vacuoles with water and nutrients. In most plant species, the highest chloroplast concentration is observed in the upper part of the mesophyll which is called the palisade, whereas the lower (spongy) mesophyll is characterised by large intercellular spaces. Thus, mesophyll cells scatter light and absorb it during photosynthesis.

However, Poulson and Vogelmann discovered that epidermal cells are also indirectly involved in photosynthesis by collecting light and focussing it on mesophyll cells without significant absorption or scattering (Poulson and Vogelmann, 1990). It means that a plant's epidermal cell could be considered a kind of "lens" for the following reasons: i) the refractive indices of its cell wall and cytoplasm differ from those of air, ii) its structures are transparent for visible light, iii) its shape. The last one varies among different plant species. Morphologists currently distinguish the following types of epidermal cells: Tabular, Papillate, Dome-shaped, Convex, Plano-convex, Conical, and Spherical (Poppinga, Koch et al., 2010; Vogelmann, Bornman and Yates,

1996; Wager, 1909). For instance, epidermal cells of *Oxalis sp.* could be considered convex lenses with a relatively large curvature radius. Such cells converge light at the focal point approximately 100 μm from the leaf surface, i.e. in the spongy mesophyll (Poulson and Vogelmann, 1990). The exact focal length slightly differs depending on where the light crosses the cell surface. Moreover, in some plants of the *Oxalis* genus, a two- to four-fold intensification of incident light by epidermal cells occurs. This could be an adaptation to the shady environment where these plants typically grow (Bone, Lee and Norman, 1985; Poulson and Vogelmann, 1990). In contrast, tropical plants that usually grow in direct sunlight have flatter epidermal cell surfaces and/or an additional layer of transparent hyaline cells under the epidermis where the sunlight is concentrated and then diffused onto the mesophyll, so that chloroplasts avoid over-irradiation (Bone, Lee and Norman, 1985). As soon as illumination changes throughout the day, including due to kin or non-kin shading, the light-harvesting system adjusts by changing the location of the chloroplasts and the amount of chlorophyll (Vogelmann, 1993). All this "machinery" should be coordinated precisely in accordance with external stimuli and the plant's own metabolic status. Different types of photoreceptors mediate responses to light of a certain wavelength. Namely, phytochrome (phyA and phyB isoforms) reacts to red and far-red light, whereas cryptochrome (cry1 and cry2) and phototropin (phot1 and phot2) activate to blue and UV light. These receptors are expressed in different tissues including epidermal, and they are essential, for instance, for photomorphogenesis, shade-avoidance response, and opening and closing stomata (Crepy and Casal, 2015; Zoulias et al., 2020). Indeed, *Arabidopsis thaliana*, a well-known model object, is able to recognise its neighbour and determine whether it is a con-specific plant using the aforementioned photoreceptors (Crepy and Casal, 2015). Furthermore, climbing plants such as *Pisum sativum* define suitable support based on their thickness (Guerra et al., 2019). Guerra et al. consider visual-based mechanisms as one of the plausible explanations for this sensing.

Summarising the facts above, we can arrive at the following conclusion: (i) the epidermis is not an auxiliary tissue, but an important plant optical system component, (ii) the sensing of visible light is involved not only in photosynthesis, (iii) there are reasons to suggest that plants detect not only relative illumination and light wavelength, but also objects.

Even the thickness sensing of *Pisum sativum* cannot constitute direct evidence for the existence of plant "vision". Nevertheless, an intriguing phenomenon that seems to be more persuasive does exist. The leaves of the Chilean woody vine *Boquila trifoliolata* are capable of mimicking up to three host leaves (Gianoli and Carrasco-Urra, 2014). More precisely, the leaves of one *B. trifoliolata* plant simultaneously mimic the leaves of three closely neighbouring plants, which it recognises as hosts. Gianoli and Carrasco-Urra, who discovered this phenomenon in 2014, postulated that *B. trifoliolata* receives information via chemical signalisation or horizontal gene transfer. However, in 2020, White and Yamashita reported on experiments with an artificial "host" vine, when *B. trifoliolata* attempted to mimic plastic leaves (White and Yamashita, 2022). Since in this case, it is unlikely that the mimicking vine could have received a volatile or genetic signal from a piece of plastic, one may also suggest the possibility of optical sensing, although this does not disprove the existence of other mechanisms of mimicry. In addition, White and Yamashita mention the experiments of Gotlieb Haberlandt, who elaborated the concept of plant ocelli (1905), and Harold Wager's experiments on the perception of light in plants (1909) (Haberlandt, 1905; Wager, 1909).

To demonstrate leaf epidermis cells' optical features, H. Wager decided to take photographs of some objects through adaxial and abaxial epidermis sections. A specimen was submerged into glycerine and placed onto a microscope's object table. The photographed object was far enough away from the tissue specimen to bring it into focus. Then, using a flat mirror, H. Wager received an image reflected on the epidermal cells and captured it with a camera. He concluded that cells with a regular shape, such as those of *Tradescantia fluminensis*, *Zebrina pendula*, *Ligustrum ovalifolium*, and *Orchidaceae gen. sp.*, form the clearest image (see Fig. 2). Wager's approach not only allows us to estimate the cells' optical features, but to visualise data and demonstrate how cells transform an image. We were inspired by this early 20th century work and decided to continue this research using modern technology that expands both research opportunities and our means of artistic expression.

Nevertheless, we highlight that it is too early to talk about the equivalent of "vision" in plants. We can only assume that plants have a system that perceives optical signals not just to sense the general level of illumination, but perhaps also to distinguish surrounding objects at some level. Such abilities are usually called optic sensing. Some optic sensing systems are considered analogous to human organs of vision. In biological terms, this means that they are at least partially similar in function. This does not mean similarity in the organisation and developmental or evolutionary origin (homology) of these systems. We should investigate the complex role of light and its optical transformation in plant biology. However, it is known that visual images are meaningful to humans, particularly as a means of communication. G. Haberlandt and H. Wager used images to represent ray transformation. We do not know if they found anything philosophical or artistic in doing this, but our team saw the potential for a bioartistic statement, not to mention the research potential.

How can we demonstrate the work of plant cells as lenses without a microscope, using a fragile tissue specimen, and in a public space instead of a laboratory? We decided to collect precise enough data about a cell's focal length and other paraxial characteristics in order to predict how this cell would transform images using a mathematical model. We then combined this digital version of a plant epidermal cell with a physical object — a sculpture with integrated tablets: on these screens, spectators could see a video that was being manipulated in real-time. The sculpture is an image or symbol of plant identity that is grounded in recent scholarship, including our own. We would like to invite spectators
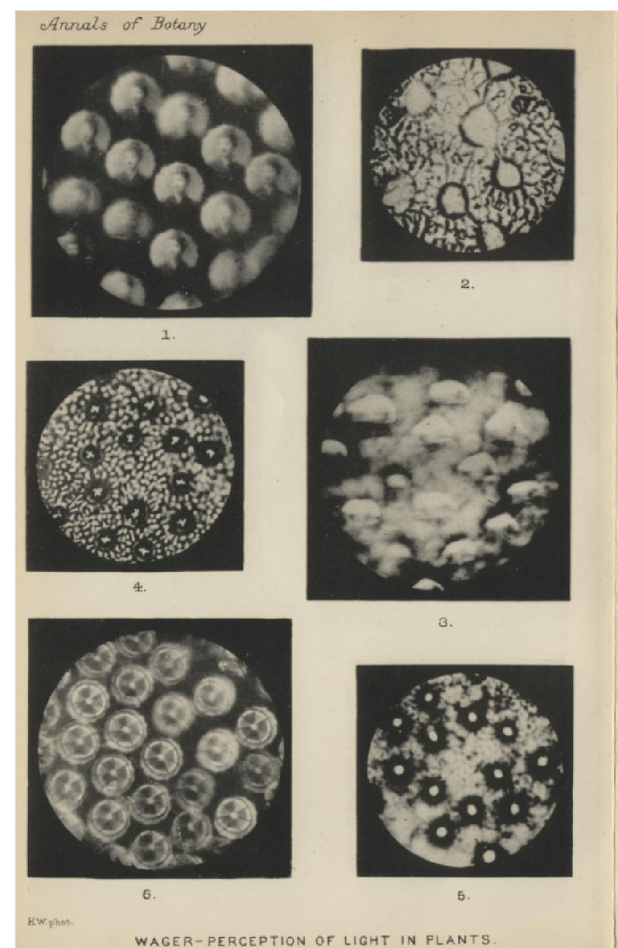

Fig. 2 Harold Wager's photographs taken through the plant epidermis. 1—cells of the upper epidermis of *Tradescantià fluminensis*, 2—cells of the upper epidermis of *Mesembryanthemum cordifolium*, 3—cells of the lower epidermis of *Mesembryanthemum cordifolium*, 4—the special cells on the underside of the leaf of *Mesembryanthemum cordifolium*, 5—rays of light brought to a focus through the granules of mucilage. These granules interfere with the passage of light through the cells as a whole and render the image almost indistinct (Wager, 1909). Public domain image.

to see themselves through the plant optics and, simultaneously, shift focus from their own reflection to the identity of the "other".

Methods and results
Homage to Wager: photographs through plant epidermal cells. Our very first experiments replicated H. Wager's method for photographing macroobjects through plant epidermal cells. According to H. Wager's results, the clearest images could be obtained with regular-shaped cells (Wager, 1909). The epidermal cells of *Tradescantia zebrina* possess suitable properties. We prepared unfixed longitudinal sections of *T. zebrina* epidermis, submerged it into a drop of water on the cover glass and then placed it on a glass slide. Excess water was removed. The upper epidermis was taken from a mature *T. zebrina* leaf. We followed by positioning the specimen on the microscope slide. Images of an eye and a portrait of Gottlieb Haberlandt were placed into a filter wheel between the aperture diaphragm and the bottom lens. To obtain images that are formed by the upper epidermal cells of the plant, an Axio Imager Z1 (Carl Zeiss) microscope with colour camera was used in transmitted light mode with a 10x
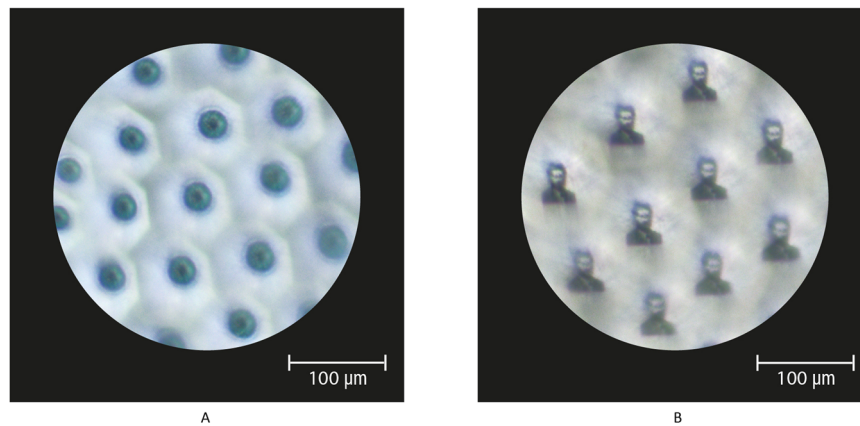
Fig. 3 The images of external macroobjects focused by a plant lens cluster. A—the image of an eye, **B**—portrait of G. Haberlandt. Axio Imager Z1 (Carl Zeiss): transmitted light mode, 10x magnification, NA = 0.2. Original image.

magnification epiplan objective, NA; = 0.2. Figure 3 illustrates images of an external macroobject focused through a cluster of plant lenses on the optical axis of the confocal microscope. Images of an external macroobject focused through a cluster of plant lenses are shown in Fig. 3A, B. Gottlieb Haberlandt was the author of the plant ocelli hypothesis (Haberlandt, 1905). Therefore we found his portrait and image of the eye to work best as an homage to H. Wager's photography (see Fig. 2, 1st panel).

Replication of early twentieth-century experiments on the optical properties of plant epidermis allows us to study the spatial structure of plant cells. We succeeded in conducting a research study revising our previous achievements and validated them using modern optical equipment. However, we applied alternative preparation options and techniques to obtain optimal results as well as colour images. Additionally, we considered the choice of image important, since an image is a communication signal, whether it is a message or an artistic statement.

***Akebia quinata*: the model plant**. Since we did not receive access to a *Boquila trifoliolata* plant, we decided to choose its close relative in order to practise our methods and set up a mathematical model. Thus, the *Akebia quinata* vine became a model object for the research. Both *B. trifoliolata* and *A. quinata* belong to the *Lardizabalaceae* family. Besides, vines presumably developed some mechanisms for the perception of the properties of their supporting structures (Guerra et al., 2019). We purchased a 2-year *A. quinata* seedling at the Plantanet nursery (Plantanet (RUS), 2022). We then grew the plant in a universal soil mix under a 13:11 light cycle following the botanist's recommendation. We used white and purple LEDs for the illumination.

Determination of structure and morphological features of *Akebia quinata* epidermal cells by confocal microscopy. First, our model required the physical parameters of plant epidermal cells, namely, their thickness and diameter. Modern methods allow us to measure these much more accurately than H. Wager would have been able to. One of these methods is confocal laser microscopy. First, it has greater resolution on both XY and Z planes compared to traditional wide-field microscopy: this way, borders between cells could be detected more precisely. Furthermore, a confocal diaphragm is not vulnerable to the issue of scattering from out-of-focus layers of the object, since a confocal microscope can scan a specimen only within a tiny focal plane. These optical "sections" could then be combined into a 3D reconstruction.
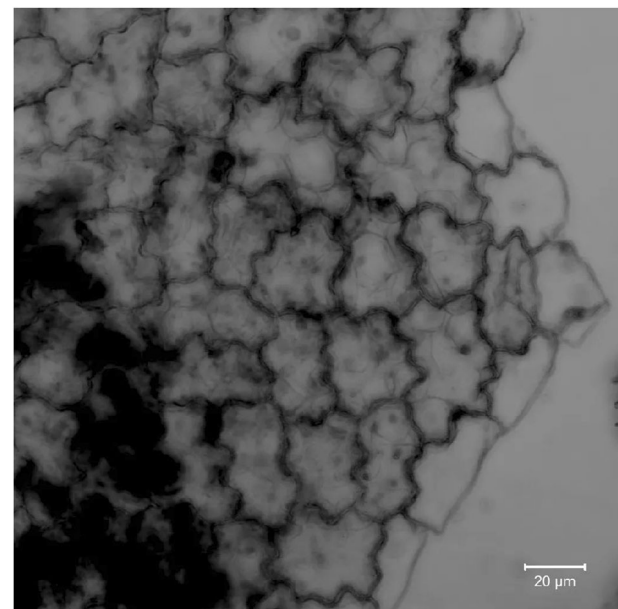

Fig. 4 *Akebia quinata* leaf adaxial epidermis. Longitudinal section. Original image.

In this study, we made longitudinal and cross-sectional cuts of *Akebia quinata* leaves using a razor blade, tweezers and a dissecting needle. Unfixed tissue sections were placed in a drop of water or glycerine between the object and the cover glass. We used an LSM 710 scanning confocal microscope (Carl Zeiss) with a long-distance 20x magnification lens (NA = 0.4) and a 405 nm laser for obtaining images of the epidermis layer in transmitted light. All morphometric measurements were performed using Zen Black 2.6 software. We identified that the thickness and diameter of *A. quinata* epidermal cells vary between 11–19 µm and 13–40 µm, respectively. As seen in Fig. 4, *A. quinata* adaxial epidermal cells are jigsaw puzzle-shaped. Figure 5 depicts a cross-section sample of the *A. quinata* adaxial epidermis, which is convex-shaped. Thus, they can be expected to function similarly to *Oxalis sp.* convex cells (Poulson and Vogelmann, 1990), i.e. be able to concentrate incident light at a focal length.

Optical parameter calculation and model setup. To predict how to plant epidermal cells would transform images, our model
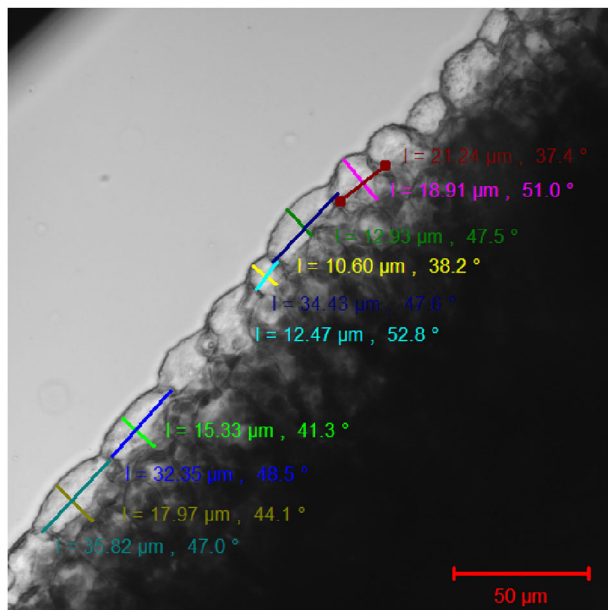
Fig. 5 *Akebia quinata* leaf adaxial epidermis. Cross-section. Original image.

should describe the paraxial characteristics of these "lenses", particularly their focal length. To calculate it, we considered the transformation of beam parameters on two spherical surfaces (the front/upper and rear/lower radius of the cell's curvature), as well as in the gap between them, and then determined the final beam transformation in the entire lens.

The law describing the transformation of a beam upon refraction on a spherical surface is in accordance with Formula 1. We have two such transformations, on the front and rear edges of the lens.

Formula 1

$$P = \begin{bmatrix} 1 & 0 \\ \frac{-(n_2 - n_1)}{R} & 1 \end{bmatrix}$$

n—refractive index of the medium, *R*—curvature radius

We assume that the epidermal cell cytoplasm is optically homogeneous, which means that the transformation of parameters can be described by Formula 2:

Formula 2

$$T = \begin{bmatrix} 1 & \frac{l}{n} \\ 0 & 1 \end{bmatrix}$$

l—the thickness of the optically homogeneous gap, *n*—refractive index.

To find the transformation matrix of a beam in a thick lens (denoted as G), it is necessary to multiply the three matrices in the reverse order of the beam passing through it. First, light passes through the rear spherical surface (the result of this transformation is denoted as P_2), then through the cell cytoplasm (T from Formula 2), and through the front spherical surface (P_1). So the final Formula 3 will look like this:

Formula 3

$$G = P_2 \times T \times P_1$$

Knowing the elements of the matrix G, one can easily find the cardinal points of the optical system, for example, the front (f_1) and rear (f_2) focal lengths of the system or the corresponding focal segments that we need.

The main focus of the optical system is the point at which all the incident rays parallel to the main optical axis are collected. The main focus can lie either to the left or to the right of the main point. The main points (H_1, H_2) are the intersection of the main planes with the optical axis. The main planes of the system include a pair of conjugate planes in which the linear increase is equal to 1. The focal segment Sf is the distance from the corresponding surface to the corresponding focus.

Let's assume that, after mathematical transformations, the total matrix of our optical system is equal to (see Formula 4):

Formula 4

$$G = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

It is now more convenient to get the necessary paraxial characteristics from the matrix M. Here, the rear focal length is equal to (see Formula 5):

Formula 5

$$f_2 = -\frac{n_2}{C}$$

where n_2 is the refraction index of the outer medium. We can then find the distance from the rear reference plane (cell surface) (see Formula 6):

Formula 6

$$t_2 = -\frac{(n_2 - A)}{C}$$

Finally, let's substitute the values in the formulas. For *Akebia quinata*:

$n = 1,36$ (Vogelmann, Bornman and Yates, 1996)
$R_1 = 27\,\mu m$ (our data)
$R_2 = 27\,\mu m$ (our data)
$l = 15\,\mu m$ (our data)
According to Formula 3:

$$G = P_2 \times T \times P_1 = \begin{bmatrix} 0,853 & 11,029 \\ -0,25 & 0,853 \end{bmatrix}$$

According to Formula 5:

$$f = 40,476$$

According to Formula 6:

$$t = 34,524$$

The model is suitable for rendering any video stream, including from a user camera, and converting it the way a plant epidermis would. In other words, it allowed us to see objects "through the cells". Our data processing scheme, including specimen imaging, calculations, and the subsequent integration of the model on the plantovers.art website is presented in Fig. 6. In the future, our model can be applied to an in-depth study of biochemical and biophysical processes underlying the mechanism of host plant leaf imitation by the *B. trifoliolata* vine.

However, there are other modelling methods that have been applied to botanical research. Xiao et al. combined a ray tracing algorithm with a programmable representation of three-dimensional leaf anatomy (Xiao, Tholen and Zhu, 2016). GPU algorithms are also a well-known approach for modelling epidermal development (Christley, Lee et al., 2010).

***Plantoverse*, the artwork: concept and philosophy.** In our *Plantoverse* artwork, we invoke the concept of the 'phygital'. It is a
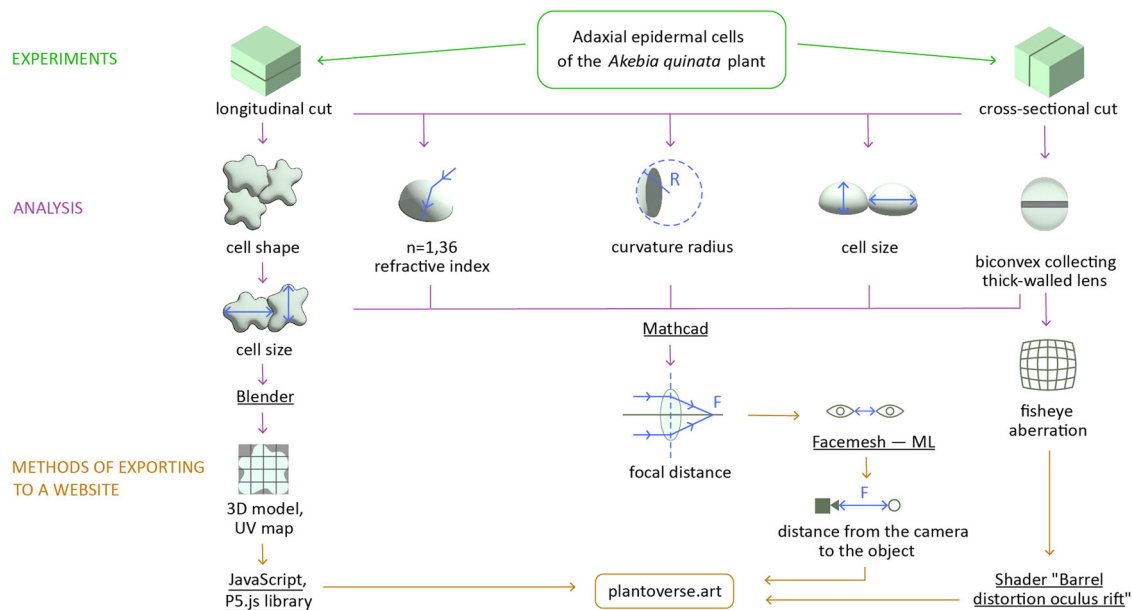
Fig. 6 Scheme for developing our mathematical model, depicting how a plant cell transforms an image. Original illustration.

term for a communication system that combines the physical and the digital (Lupo, 2021). The important thing for us was to connect the digital and the physical objects to evoke an emotional experience in the viewer and reveal the project's key concept. However, the work we do in studying and analysing the optical properties of plant epidermis leads to us adapting the collected data to a mathematical model. As a consequence, what occurs is a dematerialisation of the plant leaf at the cellular level. In curator and art critic Lucy Lippard's research on the dematerialisation of art objects, the assumption is that dematerialisation is more dependent on its interpretation and relationship to materiality (Lippard, 1997). Lippard questions whether art must have a physical presence or can exist purely as a conceptual framework for perceiving the world. Although we do not eschew physical implementation, we refer to the studied biological system mostly via process which serves as a metaphor for communication. In these terms, we are evidently part of the growing trend of emphasising audience participation and interaction (also detailed by Lippard). Moreover, dematerialisation in our case could be considered as an expansion of artistic language. We wanted to find a way to avoid exposing the object of our research itself. One of the purposes was to shift the audience's focus from the "laboratory aesthetics" of working with microscopic objects to such immaterial concepts as perception, agency, and otherness.

Dematerialisation and the absence of living matter in artwork make some authors question whether said artwork can be considered bioart (Zaretsky, 2017). Do such metaphors based on a non-living medium correspond well enough with the living systems to which they refer, without being misleading or underexpressive (Ahmedien, 2023)? Can a refusal to use living matter be justified, and the work still be considered bioart? Supporters of "genuine" bioart, one based on living systems, explain this approach by a number of factors, some of which are still unknown to us, and which we cannot completely recreate. The sheer number of unknowns, the complexity and subtlety of the system balance often enhance the metaphors used by the author both artistically and scientifically. However, it is questionable that the exhibition of living systems does not require it to be taken out of context. The experiment, which is considered the most reliable method in natural sciences, is also an incomplete reconstruction of a context. Some bioart-based artworks draw

criticism not because of their refusal to use living matter, but because, just like poorly conducted experiments, they may proceed from incorrect prerequisites and superficial knowledge of the system being studied (Wang, 2012). We agree with C. McLeod and B. Nerlich (McLeod and Nerlich, 2017) that it is important to use appropriate language to explain the world, considering that it affects the way we think about the world and interact with it. Since bioart has an inevitable connection with science and knowledge production, metaphor construction becomes a part of the epistemic process. Our responsibility was to base our work on reasonable data and not to push our viewers towards conclusions that contradict scientific discourse. However, one should not treat bioart as science popularisation since it is an artistic practice, meaning there is space for sharing and evoking emotions. There is an opportunity to ask questions, not just explain; there can be allegory, not only a metaphor. We would therefore like to emphasise that bioart contributes to the production of knowledge that differs from that of science. It can also be rational, of course — but sensual knowledge was no less epistemically important to us. Thus, our goal was to find an artistic language to share both a scientific concept and an emotional message. We took into account that Art & Science (and maybe Art in general) requires a certain awareness. We left some space for spectators' interpretations but stated our main prerequisites in the attendant text and employed mediators to field possible questions from the audience.

Concerning our emotional message, we decided to work with the idea of looking at oneself through a plant lens. Epidermal cells actually work as lenses according to certain physiological functions, although we don't mean vision in a biological sense. Yet, vision is important to humans. This is one of the main ways of gathering information about the world, at least for sighted persons. When it comes to art and science, these are, of course, also human-specific ways of knowing in which visual information has historically played a large role. This begs the question: what do people think when they accept the idea that optical sensing (evolutionarily prior to vision) is important for some species, e.g. for some animals? In particular, this leads to us using gestures and facial expressions to communicate with said species, or us caring about what the environment they

inhabit looks like. Moreover, what if we assume that plants possibly recognise us, as well as the objects we create, as part of the environment? We were fascinated with the question of whether it matters to people that there are silent bystanders around them, and it remains uncertain if we will ever comprehend how exactly they perceive us.

Physical and technical implementation. We are passionate about plants. Our goal as artists was to increase the audience's sense of awe and foster brand-new connections. We began by bringing the two worlds together as a mixture of art and technology. First, we performed the calculations and created a mathematical model. Then, we transformed our theoretical knowledge and numerical data into the artwork: a sculpture in an exhibition space and the opportunity to see oneself through plant optics digitally (via a website). The latter added inter-activity to the sculpture, revealing the work's communicational meaning.

The project's visual component is a bionic media sculpture with tablets integrated into it. The user can observe themself through plant optics on the tablet screens in real-time. The resulting image becomes a part of the sculpture, meaning that the environment it perceives impacts its appearance and eventually defines the quality of relationships between the participants of this communication. By interacting with the artwork, the viewer is supposed to develop an emotional reaction to the plants. Hopefully, these feelings will be formed, among other things, under the influence of the scientific facts underlying the installation.

Data on cell size and curvature radius of the *Akebia quinata* plant were used to develop the plant algorithm. The cell images from an LSM 710 confocal scanning microscope (Carl Zeiss) were converted into a 3D model, considering the cell's refractive index and lens thickness (Vogelmann, Bornman and Yates, 1996). Each cell had its own texture overlay (UV) settings. These affected the coordinates of the video stream when the 3D objects of the cells were implanted into the site. We exported the 3D model of the cells to a website through the JavaScript P5.js. library, a tool used to create interactive graphics and illustrations in a browser.

We came upon the fascinating 3D structures when working with the confocal microscope and studying leaf cells. These images were obtained during the reconstruction of the epidermal surface. The first attempts were unsuccessful due to the large step size in the scan: the surface of the cells did not look smooth, but instead "stepped". Although we didn't use them for mathematical modelling, these "failed" images served as inspiration for the artwork. By changing the arrangement of the objects, it is possible to provide them with a new interpretation. The Magic parametric tool in the Blender 3D software suite was used to develop a biomorphic model that displays subtle patterns of cellular structures in detail. This generation algorithm comes built-in with the software. It features RGB components that are independently produced by a sinusoidal formula. The obtained 3D parametric shape was optimised in Autodesk Netfabb Premium and exported in '.stl' format and then imported into Vectric Aspire 9.510 for further processing.

As soon as the word "biomorphic" appears in the text, it evokes "biomorphic abstraction" which is actually synonymous with "organic abstraction" (Biomorphic (Organic) Abstraction, 2019). The latter uses free-flowing, distinct lines and shapes that resemble those found in nature. It relates to Henri Bergson's (1859–1941) philosophy, Eero Saarinen's (1910–1961) architecture, Achille Castiglioni's (1918–2002)

design, etc. However, it was crucial for us to develop our own form and represent the images and symbols of the plant world as independent, with its own logic and creativity, rather than adhering to this style. In the designed sculpture, we express our curiosity about internal cellular structures unseen by the unaided eye (Yun et al., 2019). The significant difference is that the data the sculpture is based on is actually a scan of the cells. This is more important to us than the "biomorphic impression" which some artists use more as a stylistic tool. Although Donna Haraway's work is not directly associated with "biomorphism" in a traditional sense, her views on the intersection of the biological and the technological are closer to us (Haraway, 1987) (Haraway, 2003). In this case, the technological method of data acquisition affected how the biological system is represented. The method we used in reconstructing the epidermis is called the z-stack: the surface is scanned step by step, and the images are then merged. As mentioned above, too large a step transformed the streamlined "biomorphic" shape of the cell. On the one hand, it is consistent with D. Haraway's suggestion that technology has become an integral part of our existence and identity (Haraway, 1987). We assume that technologies also affect other organisms, and it could be the point where our worlds come together. On the other hand, this accidental technological intervention into plant representation is an error if we consider the scientific meaning of microscopic images. We used these images due to their "glitch" aesthetics.

Thus, the approaches described formed the basis for the two versions of the installation. The first iteration of the *Plantoverse* project (see Fig. 7A, B) was exhibited at a student exhibition in the summer of 2022. Its second iteration was presented at the *Speculum Artium* new media festival in the autumn of 2022 (see Fig. 8). This is a significant event for the Art & Science community, which has been held in Slovenia since 2008, so its audience is discerning and informed. The versions of *Plantoverse* differed not only in colour, but also in production technique. In the second version, we found a better way to convey the pattern that fascinated us while working with the microscope. However, the audience deemed the first sculpture intriguing and thought-provoking as well.

***Plantoverse*: plans for the future**. After the *Plantoverse* project was exhibited, we reflected on its further scientific and artistic potential. We are searching for new spatial solutions to bring the audience to a more equal footing in communication and to develop unconventional floral aesthetics based on scientific data. There are also plans to improve the *Plantoverse* platform and refine the mathematical model describing the optical properties of the adaxial leaf epidermis of the *Akebia quinata* plant. Namely, the data on the focal distance to the object is supposed to be implemented using "Facemesh" distance analysis, a machine-learning model that allows the recognition of facial landmarks in a browser. In this way, the distance from the camera to the viewer can be analysed in real-time. This means that the image of the viewer will come into focus only when the object is in the area of focus of the lenticular epidermal cells. As a result, we can achieve a more accurate representation of the optical properties of epidermal cells. Besides, we want to add new "spaces" to planto-verse.art, which would clearly explain various intriguing features of the plants. Hopefully, this will aid in the emergence of alternative criteria and norms for contact with plant organisms.

Conclusion

The *Plantoverse* project explores the possibility for empathy not only towards humans but also to plants. Because of lack of
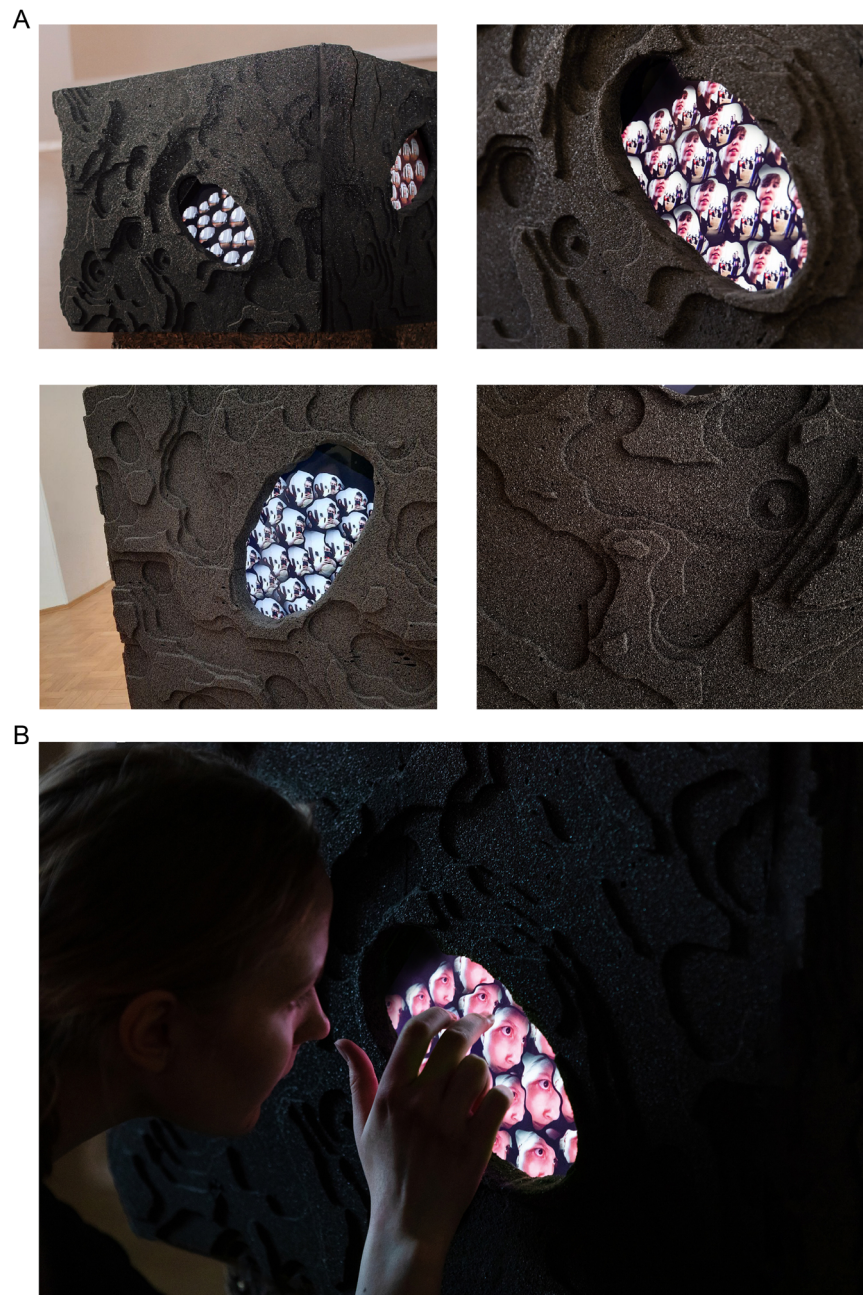
Fig. 7 Details of the foam glass sculpture. Made by a CNC milling machine (**A**). Original image. Interaction with the first version of the installation (**B**). Original image.

awareness about plants, there is a tendency to downplay their importance, so it was essential for us to address the phenomenon of *Plant blindness* and the potential problems associated with it. We also wished to convey the emotions we experienced when immersed in the world of flora. Therefore, we examined the plants both biologically and artistically. As a result, we created a biomorphic media sculpture performing the functions of a digitalised biological system. We based *Plantoverse* on data describing the optical features of leaf epidermal cells and their physiological meaning. The audience can look at themselves through plant "lenses" while interacting with the installation. Hopefully, we managed not only to educate the audience but to touch them emotionally and challenge their views about plant sensitivity. We also aimed to represent plant identity: plants are modular creatures that mix

decentralisation and non-hierarchy, choosing their own life strategies. Both the physical plane, or the plane of abstraction, and *Plantoverse*'s digital world represent this. Although there is a feeling of strangeness and the unknown, it draws us in rather than alienates us.

Hypotheses underlying our work require further research, but these already prove a sufficient cause for discussion about the plant sensory system and an understanding of plant biology that has developed in humans. It doesn't mean that we will discover plants' eyes, vision, and consciousness that are typical for us. This is the otherness we must accept in order to be conscious of plants and compassionate towards them. We believe that this will facilitate a shift from an anthropocentric attitude towards one where plants are equal agents in a multispecies system.
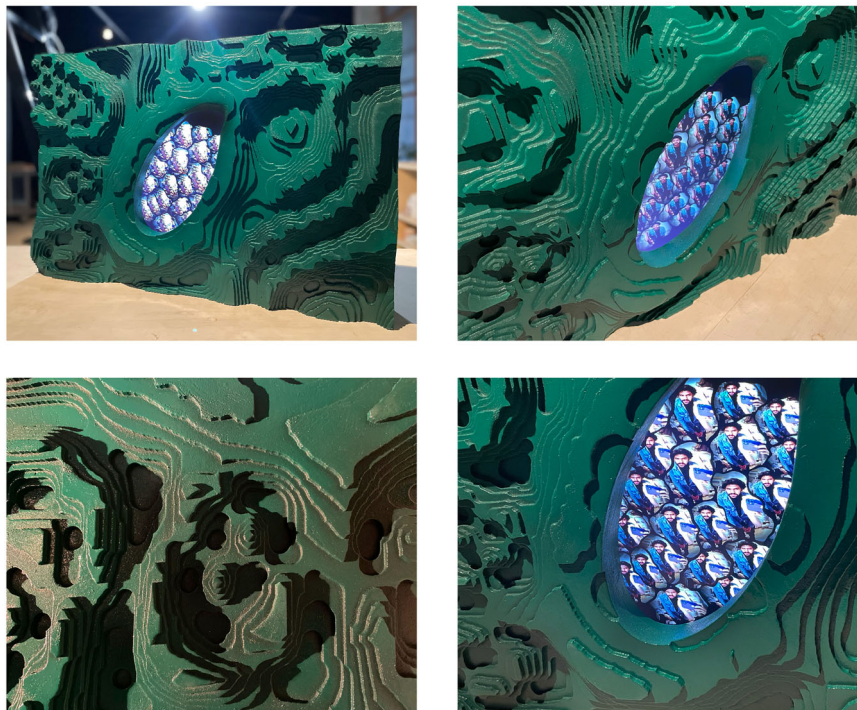
Fig. 8 Details of the plastic sculpture's creation. Made by a CNC milling machine. Installation in the exhibition space. Original image.

Data availability

The primary data generated and analysed during the current study consists of images from confocal and wide-field microscopes. They are available from the corresponding author upon a reasonable request and could be analysed according to described methods. No other data was generated in this study.

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Author contributions

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Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Correspondence and requests for materials should be addressed to Alexandra Burnusuz.

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