Patterns and Opportunities for the Design of Human-Plant Interaction

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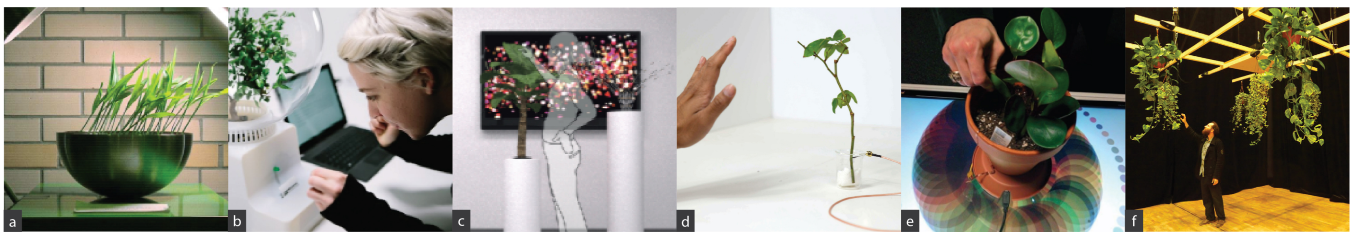

Figure 1: Representative Human-Plant Interaction research projects employing different System Architectures, Plant I/O Coupling, Plant Manipulation Techniques, Application Contexts, and Scales (of deployment): a) Infotropism [57], b) Project Florence [122], c) Botanicus Interacticus [109], d) Cyborg Botany [114], e) Touchology [116], and f) Akousmaflore [81]. All images used with permission.

ABSTRACT

The emergence of living organisms as entities in HCI presents an opportunity to collaborate with other beings through technology, align interspecies motives, and nurture greater empathy for the non-human. Plants are particularly interesting because of their natural ability to sense and respond to environmental stimuli and potential to enable more sustainable interaction design. However, due to the cross-disciplinary and emerging nature of this space, there is a need to identify overarching patterns and discern opportunities for unifying future research. This paper aims to systematically analyze existing Human-Plant Interaction (HPI) works by presenting a survey of projects across HCI, art/design, architecture, and bioengineering. We identify core design paradigms along the dimensions of HPI System Architecture, Plant I/O Coupling, Plant Interfacing and Manipulation Techniques, Application Context, and Scale. From these themes, we assemble a framework for HCI practitioners to approach HPI, and discuss opportunities and open questions for future exploration.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

literature review, plant-integrated HCI, human-plant interaction, living empathetic media, biodesign, sustainability

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1 INTRODUCTION

Recent reports by the Intergovernmental Panel on Climate Change [12] indicate that previously projected systemic disruptions, including extreme weather, flooding, and arctic ice reduction, are proceeding faster than predicted and with increasing volatility. At the same time, owing to their key role in sustaining a large portion of Earth's biodiversity and effective carbon removal capabilities, forests, grasslands, and other plant-dominated ecosystems are consistently referenced by environmental advocates as keystones in curbing the worst effects of the climate crisis [80, 138]. Yet, it is these same ecosystems that we continue to lose—at the rate of roughly one football field per second [11]—due to agricultural and industrial demands [6]. The industrialization of society sparked the development of a primarily extractive way of living that has percolated up till now, one symptom of which is our regular reliance on the rapid and indiscriminate harvesting of raw materials to feed artificially-generated demand. This normalized practice has put the needs of humans and plants at increasing odds with each other for at least two centuries.

Happily, the emergence of living organisms (such as microbes, plant roots, leaves, and mycelium) as systems for technological integration or collaboration in HCI presents a plausible alternative to this conundrum—a way to, all at once, potentially popularize biocompatible materials, collaborate with nature through technology, align interspecies motives, and nurture greater empathy for the non-human. Indeed, interest in nature-integrated technology and ways of design thinking have surged as of late, as evidenced by design firms like Space10 publicly committing to a "people-planet approach" [10] and nationally-backed art initiatives, like Germany's Driving the Human, initiating open calls themed around "sustainable cohabitation" [9].

Plants hold the potential to be of particular interest to HCI, not just because of their practical potential in helping us mitigate the climate crisis through unique capabilities like carbon sequestration, but also because of the ways in which their evolutionary departure from human beings may lead to more sustainable innovations and shape our future technologies and relationships with other organisms. Plants' natural abilities to sense and respond to their environments present exciting opportunities for designing interspecies interactions. Indeed, existing works have cited the opportunity for new sensing systems [73], unlocking novel ways of moving through the world [77], supporting the elderly [94], enabling improved agricultural or gardening techniques [45], and advancing slow technology and nurturing healthier human-nature relationships [70], as additional driving factors that make plant-integrated technology a tantalizing area for exploration. Past works in Human-Plant Interaction (HPI) center primarily around the implementation and evaluation of individual prototypes, including a technologically-mediated human-plant communication system [122], a series of experiments evaluating various ways of manipulating plants as information displays [26], and an exploration of human-forest interaction through the transmission of sound [70]. The majority of such projects investigate technical approaches and challenges around leveraging live plants as material components and I/O interfaces, or study the effects such artifacts have on human behavior and sentiments about nature. However, a good portion of existing prototypes approach these subjects from a human-centered angle, and are often not carried out with the intention of explicitly addressing sustainability.

Despite the possibilities that plants and plant-integrated systems present, HCI and other sciences have historically focused on, if not primarily human-centered applications, then zoo-centric applications. Gagliano et al. write that "a quick survey of the scientific literature of the last five years reveals that, on average, only one paper is published on plants for every two published on animals." Renewed awareness of this bias towards the animalistic has, in recent years, sparked scientific and cultural interest in plants' myriad sensory capabilities, unique forms of intelligence, and other high-potential characteristics (such as sensitivity to particular environmental contaminants, air cleaning, etc.), many of which bear little resemblance to our own. New dialogues around how we communicate about plants also acknowledge that our zoo-centric biases color the metaphors used to frame our understanding of vegetal subjects: "In our use of language, plants are still expected to exhibit animal-*like* qualities in order to be acknowledged as sensitive living organisms, rather than being appreciated in their own right and on their own terms" [41]. And it is such a perception that has led to not just the continued alienation of industrialized society from the plant kingdom, but a dearth of empathy for all beings that do not appear animate or intelligent based on traditional human parameters [97].

This fractured human-plant relationship becomes concerning when one considers that exposure and a connection to nature is not just fundamental to mental and physical health [140], but to our continued survival as a species. Human beings are one node in a larger network of organisms and natural processes—an understanding that Indigenous communities around the world live out every day, and that has helped them to safeguard some of the world's most biodiverse landscapes for hundreds of years [36, 115]. In contrast, industrialized society is only beginning to rediscover and consider such ideologies. Perhaps, this is where HCI, in its melding of diverse fields such as art, design, and technology, can step in. Plant-integrated technologies present an opportunity for researchers, designers, and engineers to create devices, fixtures, and possibly even system-wide innovations that are not only sustainable and symbiotic, but rekindle human relationships with the diversity of species that inhabit this earth. Could HCI plant research, through investigating new ways to work and design with living organisms, help us better understand the quality of what has been called "plantness" [58]—their many ways of inhabiting, sensing, and interacting—and in doing so, help move us towards a de-anthropocentrized future? To answer this question, it is necessary to understand the space of existing work in Human-Plant Interaction, and where it has yet to grow. Accordingly, we approached this review with the goal of probing into the following research questions (RQs):

(1) What does the system architecture for previous HPI projects and prototypes look like?
(2) What are common plant input and output "formats" for HPI projects? How do they tie in with human-plant interaction design?
(3) What has historically motivated HCI researchers and designers to work on plant-integrated projects? What are some commonly explored design intents or application contexts for HPI projects?
(4) What technical approaches have researchers employed to manipulate or interface with plants?
(5) How deeply have researchers investigated the deployment of HPI prototypes at various scales of interaction (e.g., interaction with a singular human or plant entity versus with a distributed network of plants)?

(6) How might an analysis of past work help create a systematic way for researchers to approach the design and execution of future HPI projects?

Due to its emerging as well as intersectional nature, there is a need to take stock of existing plant-based interaction research across fields and identify an overarching set of themes, tools, and opportunities for advancing such work within HCI. This review distinguishes itself from past works by providing the first cross-disciplinary synthesis of projects focusing specifically on plant-integrated computational prototypes and design techniques related to human interaction with living vegetal subjects. We present an exhaustive analysis of plant-focused projects relevant to HCI, breaking them down into themes which elucidate how HPI prototypes are constructed: 1) **System Architecture**, 2) **Plant I/O Coupling**, 3) **Plant Interfacing and Manipulation Techniques**, 4) **Application Context**, and 5) **Scale**. We further identify challenges and opportunities within each theme and assemble a framework elucidating how to approach the space of HPI. We conclude our review with a discussion of pertinent open questions and ethical considerations regarding plant agency, anthropomorphism, symbiotic technological systems, and opportunities for future work.

Previous papers have brushed upon a subset of these topics, but typically in an animal-focused or human-centered context. We aim to complement these works by highlighting plants as a collaborative entity and focusing on literature involving interaction with living plant subjects. Our review aims to aid HCI researchers in understanding the breadth of existing work and provide them with a variety of functional and design elements at their disposal when conceptualizing and constructing HPI artifacts. It is our desire that readers come away inspired to further technologies for enabling mutualistic human-plant interactions, and curious about the possibilities that lie beyond.

2 RELATED WORK

2.1 Review and Vision Papers Regarding Multispecies HCI

While there have been no previous reviews focused specifically on plant-integrated works in HCI, past literature features proposed visions for multispecies HCI and syntheses of closely-related design spaces. Pataranutaporn et al. proposed the concept of "living bits" in their work, presenting an overview of existing prototypes and a proposed design methodology regarding the deliberate incorporation of living microorganisms into HCI [106]. In their examination of HCI works for the garden, Rodgers et al. acknowledged the opportunity to use such technologies to explore activities that extend beyond gardening and into "interaction with plants and animals" [112]. One such extension includes what Kobayashi dubs Human-Computer-Biosphere Interaction (HCBI), a vision of computing that enables interaction between humans, computers, plants, and wildlife [70]; the majority of projects presented in this work use audio as the main medium for interspecies communication. Another example is McGrath's piece on "species-appropriate computer mediated interaction," which motivates creating systems that enable "a non-human to interact with a computer in a (species-specific) meaningful way" [95]. The author points out that common design frameworks are tailored for human needs and often unsuitable or insufficient for other species. Indeed, for such interfaces to function, the virtual "must be translated to and from their species-specific input/output and tasks." Other visioning pieces remark on the changing landscape of interaction design in the face of living materials [96] and movements like DIYBio [105], or outline the potential of bio-integrated computing to create interactions that engender empathy for nature [148] or societal and social issues [25].

But, it is not just to HCI that we should be looking. Being a multifaceted and broad research interest, HPI is an area that benefits from cross-pollination. In the architectural domain, a number of works [45, 55] review technologies and approaches for constructing living buildings and other forms of bio-integrated urban infrastructure, referencing prototypes that harness plants for their structural and energy-producing capabilities. It should be noted, however, that many of the projects reviewed in such works are centered around construction or mechanical make-up, and do not necessarily emphasize human interaction or computation.

A separate body of related scholarship concerns reflections on and design theories around interspecies collaboration. Examples of such work include Kim Tallbear's "An Indigenous Reflection on Working Beyond the Human/Not Human," in which she remarks on indigenous philosophies and attitudes towards the interconnectedness of humans and nature. "Indigenous peoples," she writes, "have never forgotten that nonhumans are agential beings engaged in social relations that profoundly shape human lives" [124]. Within HCI, researchers have tried to address the growing distance between humanity and nature by proposing new paradigms like More-Than Human Centered Design [29] or reflecting on ways to decenter humans within design practice [101] and embrace hybridity [117].

To our knowledge, however, there have been no reviews in HCI focusing specifically on in-vivo plant configurations and their interactions with human and non-human entities. Assembling a clear picture of HPI is further made difficult by its cross-disciplinary nature and the technology required, much of which draws from fields like materials science, agriculture, horticulture, and bioengineering. We attempt to bridge this gap and bring in perspectives from fields outside of HCI to paint a clearer picture of previously-employed HPI design paradigms, with the intention of shedding light on the investigative opportunities they present for the HCI community at large.

2.2 Guidelines and Opportunities for Working with Organisms and Organic Materials

It is important to acknowledge that the investigation of bio-based materials for fabrication and design practice within HCI is not a novel undertaking. Many works which explicitly identify as falling under Sustainable HCI (SHCI), as well as those centered around biodesign, have explored a multitude of living material options: mushrooms [48, 103], mycelium [66, 83], kombucha SCOBY [79, 100] and algae [17, 123], to name just a few. To be sure, the inherently compostable and biocompatible characteristics of such organisms are highly motivating factors for their application. However, outside of projects focused on subjects like empathetic living media [25], most explorations inevitably necessitate applying techniques to halt the growth of the organism in question, typically by killing it altogether. This is understandable, especially given the aim of fabrication projects to produce artifacts of a desired, fixed shape. This work, however, distinguishes itself by focusing specifically on prototypes intended to integrate with *living* plants. We set this parameter because we are curious about the capability of living technological configurations to enable mutualistic configurations between humans and plants, and the ways in which such systems might allow us to tap into the inherent sensing abilities and intelligence of nonhuman organisms.

Within HCI, there have been a number of works involving field/case studies and design probes for identifying rough design guidelines for multispecies HCI and working with living materials. Aspling et al. [16] conducted a combination ethnography, literature review, and case study of plant interaction in computing and design (using cherry blossoms as their case study) to better understand plants as users in computing contexts. The authors conclude that if plants are to be treated as equal participants, researchers must understand what plants both desire and require, positing that supporting active plant interaction means designing to encourage plant dissemination. Evidently, this work emphasizes the philosophical motivations and implications of working with plants. Our review, in contrast, examines HPI works from a systems architecture angle, placing greater emphasis on artifact construction and implementation. In their work on decomposition in design, Liu et al. [86] analyze multi-disciplinary examples of applying decomposition as a design element, using these case studies to propose methods for leveraging non-anthropocentric design practices and discussing their implications. Although not explicitly concerned with plants, this work shares some of the ideological goals of our paper: to help "translate nonanthropocentric theories into actual design practices" and enable "co-creation that invites nonhumans to participate, sometimes even to take over the original composition." In Design for Collaborative Survival, Liu et al. [85] investigate an analogous concept of "post-anthropocentric design," using design probes to highlight tactics designers can apply to create "systems that prompt humans to notice and become compassionately concerned with the wellbeing of nonhuman species." Although the authors focus on human-fungi relationships, the themes identified (engagement, attunement, and expansion) apply equally to human-plant relationships. Finally, Kuznetsov et al.'s field study of professionals who work with nature [77], reflects on ways in which "everyday biomarkers" can be harnessed as non-digital sensing mechanisms to "teach new ways of seeing," provide low-fidelity signals, and support engagement with "phenomena that are difficult or impossible to sense with 'naked' human perception." Just as the authors performed their field study to "expand the current landscape of sensing to include living organisms," so too did we conduct our review in the hopes that outlining the landscape and tools within HPI may expand accepted paradigms of interaction beyond classic human-centered configurations.

Where systematic approaches to working with plants are concerned, prior work tends to focus on subsets of the implementation process or the broader context of such prototypes. In describing their vision of Cyborg Botany, Sareen et al. [114] distinguish their approach by highlighting that cyborg botany interfaces "with capabilities inside the plants themselves to establish bidirectional input-output," as opposed to classic HCI methods which rely upon external electronic components. The framework presented in this paper creates further delineation between existing plant system architectures by making a distinction between approaches that integrate plants and peripheral computation indirectly, by proxy, or directly (see figure 3). At the other end of the spectrum, Kuribayashi et al.'s I/O Plant toolkit [73] offers not one, but 11 different patterns for interfacing between electronics, plants, animals, and environments. However, these patterns are highly specific and tailored to the contents of the toolkit in question. Our frameworks, in contrast, aim to function as generalizable models for the overall configuration of HPI prototypes, and may act as super-sets of the patterns proposed within I/O Plant. Finally, as mentioned above, Kobayashi et al.'s outline of HCBI [70] includes a model for contextualizing and contrasting the various levels of interaction between human, computer, animal, and biosphere. We extend this approach to HPI and include in our framework an analogous model that helps researchers understand the various layers of scale that may apply to HPI artifacts. As illustrated, past works trend towards describing general design principles for working with non-human materials or present frameworks tailored specifically to plant-computer interfacing. There is a need for an overarching model that guides researchers in prototyping with plant systems in practice and breaking down the process end-to-end. This work addresses that gap through our identification of five core themes in HPI prototyping and synthesis of patterns and trends thereof.

2.3 Sustainable HCI

The potential to unlock more sustainable technologies, as well as establish human-nature relationships that enable reception to such innovation, is a large part of what makes the study of plants within HCI attractive. Naturally, then, it would be remiss not to mention Sustainable HCI (SHCI), a subfield coined within Eli Blevis' seminal work [20], which regards sustainability as the central focus of designed interactions and artifacts. In his paper, Blevis makes a case for the need to put sustainability front and center within interaction design and, through the introduction of a rubric for evaluating the sustainability potential of research projects and a set of guiding design principles, presents a plausible angle for doing so in practice. While we are not explicitly using the guides presented in his work to evaluate an outcome or rate an artifact, we find that the key motivators of this paper align with the tenets Blevis lays out to justify the framing of sustainable interaction design (SID). If one considers design "an act of choosing among or informing choices of future ways of being," then we need frameworks to help designers think about sustainability as a design value, methods that integrate those concerns into practice, and ways of reasoning that evaluate design with respect to sustainability. Accordingly, we see partnering with plants in HCI as an inherently environmentally-conscious act—*if* executed mindfully and with care. By examining the status quo of plants in interaction design and providing a set of frameworks for understanding and constructing HPI artifacts, we hope to help designers better understand how vegetation, as a natural bounty, might lead to inherently sustainable user behaviors and biocompatible technologies.

A number of other works have similarly researched and reflected on HCI practice through the lens of sustainability. Mankoff et al. [91] propose two themes: *sustainability through design* and *sustainability in design* for HCI. The authors remark that "information technologies…may form an effective channel for intervention in the everyday decisions and mindsets that play a large role in the generation of greenhouse gases," and further divide such interventions into those that enact change at the individual, group, and societal levels. Remy et al. [111], on the other hand, tackle evaluation methodology, pointing out that while the SHCI community has noble intentions, existing approaches for evaluating the success of prototypes in a sustainability context are insufficient for proving efficacy and credibility. The authors examine past evaluation strategies within the two themes identified by Mankoff et al. and suggest that researchers should continue to learn from other disciplines by understanding and adapting their methods. In a similar vein, Hansson et al. [50] sought to evaluate progress within SHCI by classifying a decade of SHCI research within the context of the United Nations' Sustainable Development Goals (SDGs). The authors reveal that 80% of the 71 papers reviewed fall under a single SDG—that of "negotiating… individual resource consumption in the home through informed choices or persuasive systems"—and that such results raise an important question: "Does Sustainable HCI really explore the intersection of sustainability and HCI, or does it only explore a narrow sliver of that intersection?" Building upon these considerations and open questions, this work attempts to understand how HPI might contribute to broadening sustainability through and in design by synthesizing techniques and prototypes across various fields.

3 METHOD

To assemble a comprehensive picture of existing work and trace overarching patterns, we performed an analysis of HCI-relevant literature published via such journals and conferences as CHI, DIS, Science (Science, Science Advances), SIGGRAPH, TEI, UbiComp, SenSys, American Chemical Society (Nano Letters), and The Royal Society (Interface Focus). Searches were limited to works published since 2005, as keystone technologies and design theories surrounding HPI have only become prevalent in the last two decades or so. To illustrate, the first international synthetic biology conference, Synthetic Biology 1.0 [1], was held in 2004, while Blevis' seminal work [20], which is often credited for originating the term SHCI, was published in 2007. We used an approach analogous to that employed by Narvaez et al. [131] for our systematic literature review, and performed identification, screening, and eligibility checks to unearth pertinent HPI work. An overview of our procedure is detailed in the form of a PRISMA [104] diagram in Figure 2.

3.1 Phase 1: Identification

We began our search with full-text queries in the following databases: ACM Digital Library, IEEE, and SpringerLink, with Google Scholar acting as a tracing tool for obtaining relevant works referenced in papers obtained from the aforementioned databases. We purposely strove to not limit searches to venue or field, owing to the cross-disciplinary nature of HPI. Table 1 lists the search strings used for each database.

We retained the results of each query according to the following guidelines:

- Query procedure and filters: All queries were run using the advanced search functions provided by the database. Results were sorted by decreasing relevance and limited to research articles published since 2005.
- Limiting results:
  - If the query returned less than 400 references, all results were retained for screening.
  - If the query returned more than 400 references, the first 400 were selected for further screening, while the next 100 were manually checked for relevance (based on titles and abstracts) to ensure coverage.

Overall, with the aforementioned rules applied, we identified 852 papers across all three databases. Tracing citations and references from this corpus resulted in another 59 papers being included for screening, resulting in a total of 911. After removing 10 duplicates, a total of 901 records proceeded to the screening stage.

3.2 Phase 2: Screening

During the screening phase, we pruned the corpus for further evaluation based on form and content (title, abstract, and metadata).

- **Form.** Papers must be research articles published in peer-reviewed venues, written in English, and available in full text format.
  - An exception was made for working prototypes, design research artifacts, or art installations previously referenced by a research article in our corpus. Outside of this criteria, we excluded alternative formats like posters, late-breaking work, and demos.
- **Content.** Title, abstract, and/or metadata must adhere to the following:
  - Mention terms related to plants, nature, gardening, agriculture, or a specific species of botanical subject, and imply that the focus is either investigating or enabling live-plant-based modes of human-nature or human-plant interaction.
  - Suggest that the work either 1) conceptually explores the design space of HPI, human-nature interaction, or inter-species collaboration, or 2) introduces a concrete prototype or technology that is designed for or possesses the potential for human-nature engagement. As such, works that centered around plants, but did not meet the interaction criteria (e.g., leveraging ML for better plant classification) were excluded.

Overall, we removed 780 irrelevant papers during this stage, leaving a corpus of 121 works for full-text examination.

3.3 Phase 3: Eligibility

During the eligibility paring process, three raters independently evaluated a subset of the corpus by reading the full-text versions of selected articles and including or excluding them according to the following guidelines:

- If the work centers on a prototype or case study:
  - One or more organisms from the plant kingdom must be treated as core material components of the physical artifact. The live plant component must be vital to the project; it should not be possible to replace it with an artificial plant and have the setup work as intended.

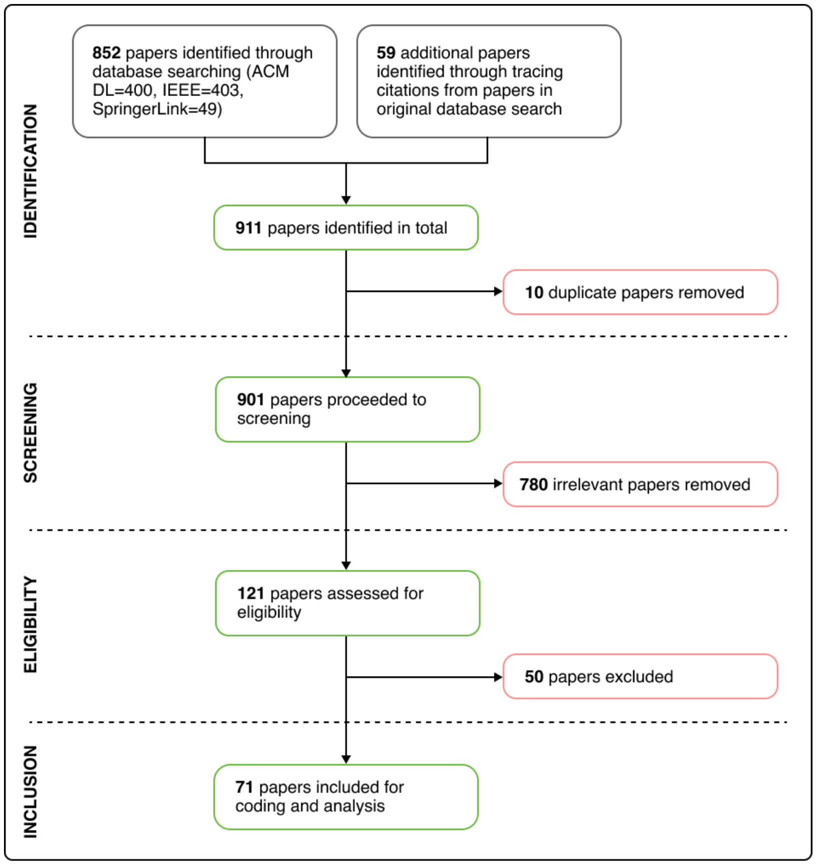


Figure 2: PRISMA diagram of our SLR process.

Table 1: The query strings used in each database searched.

Database	Search String	Filters	Num Results
ACM DL	{AllField:("plant" OR "biodesign" OR botan*) AND AllField:("HCI" OR "interaction" OR "architecture") AND AllField:(-"power plant")}	*Format*=PDF *Type*=Research Article *Year*=2005-2022	3568 (400 taken)
SpringerLink	"plant " AND "interaction" AND (biodesign OR botany OR botanical OR architecture) AND NOT ("power AND plant")	*Type*=Chapter *Language*=English *Subdiscipline*=User Interfaces and Human Computer Interaction *Year*=2005-2022	2037 (403 taken)
IEEE	("All Metadata":plant) AND ("All Metadata":interaction) AND ("All Metadata":botany OR "All Metadata":HCI OR "All Metadata":interface OR "All Metadata":architecture OR "All Metadata":biodesign) NOT ("All Metadata":"hydropower" OR "power plant" OR "All Metadata":"power plants" OR "All Metadata":"plant management") AND ("Index Terms":"sustainable HCI" OR "Index Terms":"human computer interaction" OR "Index Terms":"botanical HCI")	*Year*=2005-2022	49

   – The project must feature or potentially enable interaction between plants and humans. This configuration may be more plant-centered or human-centered, depending on the project.
- If the work proposes a fabrication process or new technology:
   – The core material being manipulated must be live vegetation, and the fabricated object must continue living even after fabrication is complete.
   – The process of fabrication must necessitate human involvement or result in an artifact that enables, encourages, or necessitates human interaction.
- If the work is a review, design, or visioning paper, the focus must be on techniques, applications, or frameworks relevant to enabling, reflecting upon, or changing human interaction with and/or relationships with plants.

Accordingly, we did not cover projects interfacing solely with non-plant, non-human media like fungi or microbes, nor did we include those that use artificial plants or plants as part of the ideation (but not the prototyping) process.

At the end of the individual review process, the raters regrouped to review selections; each person shared their work and justified their ratings to the others. Works that met with divided opinions were reviewed by at least one additional rater, who then deliberated with the original reviewer until a consensus was reached. At the end of this process, a final corpus of 71 papers remained and were included for more involved analysis, as shown in Table 2.

3.4 Phase 4: Inclusion

With the final 71 papers selected, the first author then created an initial code book (described in Table 3), which reflected aspects of the aforementioned research questions the team wanted to learn more about. Three raters independently coded subsets of the corpus according to this set of themes.

After an initial round of analysis, the team came together to discuss preliminary findings and revisit the rating schema. During this stage, it became clear that several aspects of the existing code book were problematic. For instance, "plant interaction modality" was found to be too vague, the term conflating the technical approach

Table 2: Final corpus of 71 papers included for further analysis. HCI: Go and Grow [21], BioMedia for Entertainment [113], My Green Pet [61]. Bio and electrical engineering: Compliant plant wearables [99], Mimosa pudica [135], Electronic Plants [118]. Art and Design: Pieces for Plants [93], Digital biofabrication to realize the potentials of plant roots [149], Augmenting a Human-Plant-Data Assemblage [143]. Architecture and Robotic Control: Autonomously shaping natural climbing plants [136], Evolved Control of Natural Plants [56], Plant Prosthetics [128].

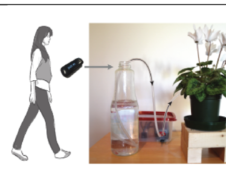
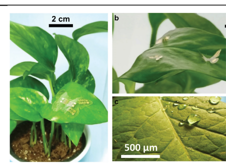
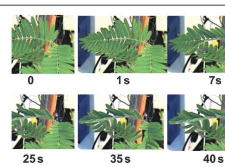
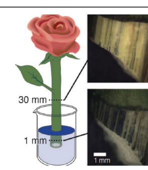
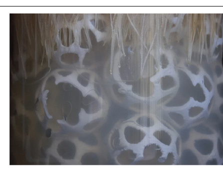
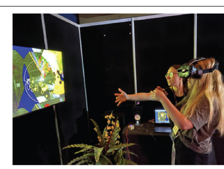
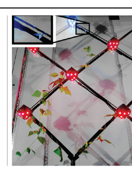
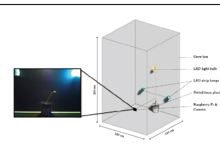
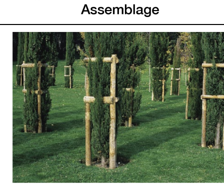
Field	Representative Papers			References
HCI	 Go and Grow	 BioMedia for Entertainment	 My Green Pet	[14, 15, 19, 21, 23, 24, 26, 27, 31–34, 38, 40, 42, 46, 49, 57, 59–61, 65, 69, 71–74, 76, 87, 92, 94, 108, 109, 113, 114, 116, 120, 122, 125, 126, 133, 144]
Bio & Electrical Engineering	 Compliant plant wearables	 Mimosa pudica: Electrical and Mechanical Stimulation	 Electronic Plants	[13, 28, 30, 43, 44, 62, 63, 67, 75, 78, 98, 99, 118, 119, 129, 135, 139, 142]
Art & Design	 Pieces for Plants	 Digital biofabrication to realize the potentials of plant roots	 Augmenting a Human-Plant-Data Assemblage	[5, 16, 81, 93, 143, 149]
Architecture & Robotic Control	 Autonomously shaping natural climbing plants	 Evolved Control of Natural Plants	 Plant Prosthetics	[47, 56, 128, 136, 137]

Table 3: Themes that comprised our initial code book.

Code	Definition	Dimensions
Plant Interaction Modality (Input)	Natural (documented in nature) plant input capabilities leveraged by this prototype.	Light, sound, touch, color, movement, other, N/A
Plant Interaction Modality (Output)	Natural (documented in nature) plant output capabilities leveraged by this prototype.	Color, texture, movement, secretion, shape, other, N/A
'Seamlessness' of Integration with Nature	Does the interaction flow of the prototype match nature? Would this interaction feel out of place in the wild?	Yes / No
Biocompatibility Level	How did the researcher intend for this prototype to be integrated or assimilated into the environment?	Bioinspired, biomimicry, bio-embedded, bioaugmented
Technical Approach(es)	Concrete techniques or engineering approaches applied during the construction of the prototype.	*This category was left open for raters to fill in freeform.*
Primary Ecosystem Interaction Level	The extent to which this prototype interacts with the external ecosystem in which it is embedded.	Environment-Plant Plant-Plant Plant-Organism Organism-Plant-Plant-Organism Environment-Plant-Organism N/A

Table 4: The final code book.

Code	Definition	Dimensions
HPI System Architecture	The configuration of the HPI artifact as a whole. Elucidates how the plant and non-plant components of the HPI prototype were set up to interface with each other.	Indirect integration Proxy integration Embedded direct integration Augmented direct integration
Plant I/O Coupling	How the HPI system relayed input (touch, light, etc.) to and induced output (e.g., shape change) from the plant subject. In other words, the plant's I/O with respect to the prototype.	In: Light, Moisture, Sound, Gravity, Touch, Vibration, Chemicals Out: Movement, Release of Chemicals, Color Change, Shape Change
Plant Interfacing and Manipulation Techniques	The primary technical approaches used to implement the prototype. This category also includes potential technical innovations that demonstrate promise for HCI, such as synthetic biology.	Plant Biomechanics, Traditional Computing, Chemistry, Material Science, Synthetic Biology
Application Context	The underlying motive for an artifact's design — the intention behind the system's creation, or the social or societal context in which it was meant to thrive.	Human wellbeing, Sustainable product design, Agriculture & Gardening, Interspecies Empathy, Bio-integrated City Technology, Societal & Environmental Awareness
Scale	The extent to which an artifact was meant to be deployed within the application context of choice, and the reach of its intended interaction with the surrounding ecosystem (e.g., artifacts might be designed for single human-plant use in an isolated lab environment or for integration into the local ecosystem).	(More than one may apply to a project) Human-Plant Human-Forest Plant-Forest Forest-Ecosystem Plant-Ecosystem

used to interface with live plants, and the design outcome or appearance of the device itself; the category also inherently assumed that prototypes were created with the intent of being seamless with nature (which does not apply to most projects) and that the plant's natural traits were indeed being taken advantage of (a rare characteristic in many of the works examined). Additionally, of the selection of traits raters were given to choose from (color, texture, movement, secretion, shape), only shape and color were found to be applied in practice. On the other hand, "primary ecosystem interaction level" was defined too tightly to apply to most prototypes evaluated; engaged discussion revealed that the category would benefit from a larger scope and more generalizability. Other code terms, such as "biocompatibility level," were found to be subsets of larger themes of interest (e.g., the design intent behind the artifact).

From these observations, we collectively reworked the terms and definitions used, and created a revised code book (described in Table 4), according to which the corpus was re-coded. This schema became the basis for the five themes we identify in this paper as representing the overarching design paradigms and opportunities within Human-Plant Interaction: 1) HPI System Architecture, 2) Plant I/O Coupling (We extend this category from its definition in the code book to also describe the "Interaction Modality" of HPI artifacts—how users may choose to interact or engage with the overall designed system), 3) Plant Interfacing and Manipulation Techniques, 4) Application Context, and 5) Scale.

In the following review, we discuss the attributes of each of these dimensions, as well as broad patterns among existing work and opportunities for further exploration.

4 HPI SYSTEM ARCHITECTURE

We begin our review by describing the gamut of overarching design configurations assumed by artifacts in HPI. **HPI System Architecture** here refers to the ways in which a physical prototype's construction is rigged to interface between the outside world, the technological system (any non-organic, non-plant components necessary to implement the artifact), and the plant system (the live vegetal subject and its corresponding sensory capabilities). On the whole, we observed four primary approaches: indirect integration, proxy integration, embedded direct integration, and augmented direct integration (see figure 3).

Indirect integration involves using classic HCI techniques and technologies (e.g., silicon-based sensors and microcontrollers) to mediate or simulate interaction with plant species; however, no component interfaces directly with the plant itself, despite its featuring as a primary element of the physical and visual design. Any sensing technologies employed tend to take a roundabout manner, focusing on environmental factors meaningful to the plant's sensory capabilities (e.g., air quality, moisture content) and relaying this data to computational systems that generate human-detectable feedback by way of digitally-generated output like pixels, sound, or light. An example of an indirect configuration includes The Pet Plant [94], which investigates the efficacy of an electronically-enhanced pot containing a live plant as a solution for boredom, loneliness, and stress in the elderly. Although the pot serves as the sole medium for interaction in this work (while the plant plays a passive role), the authors emphasized the importance of having a living vegetal subject due to both social acceptance and therapeutic health reasons.

While works that fall under indirect integration omit the plant subject from the system architecture, those that use proxy or direct forms of integration interface actively with the plant partner in some way, shape, or form. **Proxy integration** involves manipulating environmental factors known to affect the plant material, in order to trigger a desired natural response. This response is typically a human-detectable property, and meant to bring attention to some socially-significant or otherwise meaningful stimuli. One example is Babbage Cabbage [38], a project which harnesses the cabbage plant's natural characteristic of expressing various hues under certain pH conditions. The authors used data about the environment and pressing global events, among other things, to vary the pH level of cabbage growth solution, inducing natural color changes in the cabbages, which then served as visual signaling devices to human users. Another example is Plantxel [42], a matrix display composed of individual plant pixels. Each "plantxel" is made up of a *Mimosa spegazzinii*, and activated by a computer-controlled system that blows air onto the plant's leaves, causing them to open and thus produce a dark green square on the display matrix. In general, proxy approaches are not necessarily invasive to a plant's physical system or very involved. In fact, some configurations even leverage traditional gardening or agricultural techniques. The Biogotchi project, for instance, manipulates natural input like lighting to dictate a plant's direction of growth and shape it into desired forms[26]. Another example is Botanicus Interacticus [109], which turns live plants into interfaces that recognize human gestures through the use of Swept Frequency Capacitive Sensing.

Embedded direct integration, a lesser-explored technique, applies to work which physically embeds sensors or other macro-scale technologies within the plant membrane, effectively allowing devices to access a plant's inherent biological "data." The PLEASED (Plants Employed AS Sensing Devices) project [92] illustrates this through its integration of needle electrodes with live plants; the electrodes collect biosignals that when processed, communicate meaningful information about environmental factors (e.g., air pollution). Advances in sensing hardware are making embedded direct integration more and more feasible. Although not expressly an HCI artifact, Coppedè et al.'s work [28] on creating an in-vivo biosensing, textile-based organic electrochemical transistor for monitoring plant physiology is one instance of emerging research increasing the attractiveness and effectiveness of embedded direct integration for HCI practitioners. The authors' textile-based biosensor enables the detection of abiotic stress in a tomato plant. Such IoT-compatible tools are familiar to the HCI community and further enable experimentation with embedded direct integration methods in new contexts.

Finally, artifacts that take an **augmented direct integration** approach harness emerging micro-scale technologies like synthetic biology or nanotechnology to further enhance plants' abilities to interface with humans and traditional computing technologies. Due to the material properties of the technologies leveraged in augmented approaches (e.g., being on the nanoscale, being liquids, etc.), such projects are often visually seamless with respect to the outside environment and thus bring HCI practitioners closer to the UbiComp vision of ambient technology. One representative example

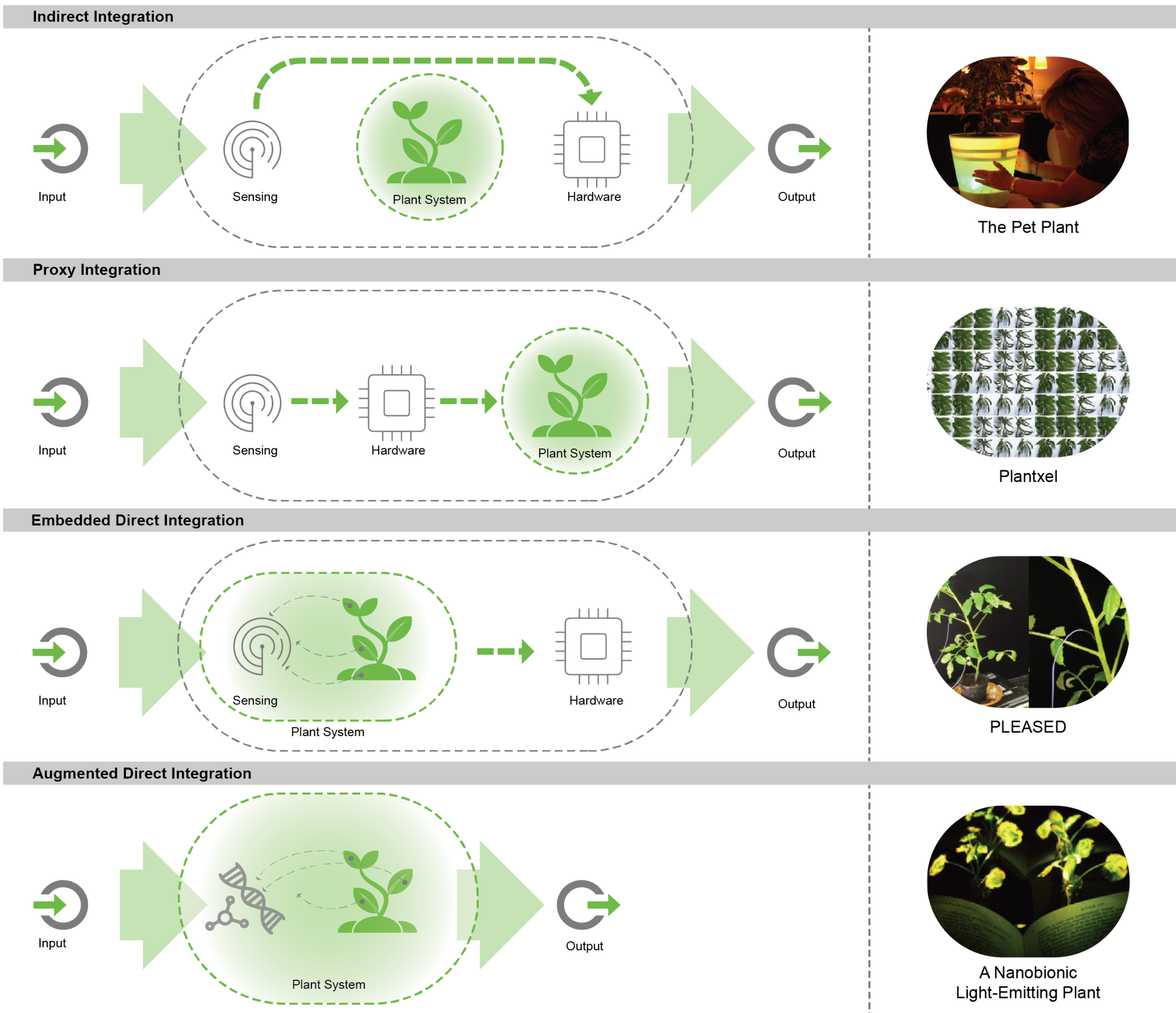


Figure 3: HPI prototype configurations can be generalized into four categories: Indirect integration (The Pet Plant [94]), proxy integration (Plantxel [42]), embedded direct integration (PLEASED [3, 92]), and augmented direct integration (A Nanobionic Light-Emitting Plant [78])

includes Cyborg Botany, which uses a conductive polymer to grow conductive wires inside plants, so they may be functionalized as antennas and motion sensors [114]. It should be noted that most augmented works (e.g., Kwak et al.'s light-emitting plant [78]) tend to fall under the domain of pure engineering and have not yet quite made it to the HCI space as a staple approach, likely owing to lack of accessibility of such technology and knowledge barriers required to effectively use them.

As a whole, the variants in systems architecture identified elucidate the most popular approaches investigators take when thinking about the high-level make-up of their prototypes; thus, in this way, we address RQ1. These architectures may serve as a blueprint for HCI practitioners seeking to create physical prototypes with live plants; researchers can use these guides to lay out a skeleton for their systems of interest and define boundaries between specific technological components or interacting organisms. While indirect and proxy integration are by far the more popular configurations in the existing literature, prototypes using embedded or augmented direct integration offer a tantalizing glimpse into the future of ambient and calm technology. As sensing and interfacing techniques from other disciplines become more widely accessible, these less-explored avenues present an exciting opportunity for the HCI community to investigate circular technologies and mutualistic configurations that treat plants as equal players in the interaction flow.

5 PLANT I/O COUPLING

Because we are interested in plants as collaborators and materials, assessing the overall interaction flow of HPI projects through the intended human-plant exchange protocol—the choice of input for

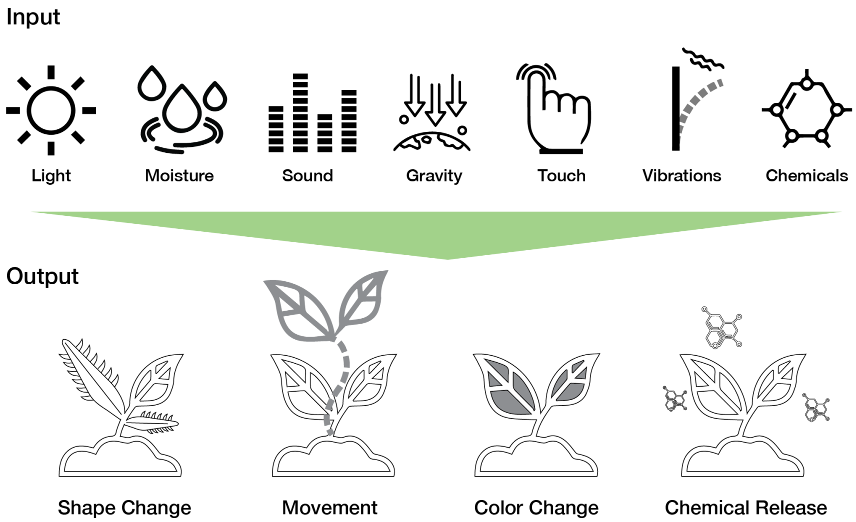


Figure 4: HPI prototype inputs can be broadly categorized as light, moisture, sound, gravity, touch, vibration, or chemical. This is not an exhaustive list, however, as plant sensory capabilities are vast and complex. Common HPI prototype outputs include shape change, movement, color change, and chemical release.

interfacing with the plant and the expected output it gives back—is important for understanding where such works fit into the conversation of sustainability and non-anthropocentrism. The overall design paradigms mentioned previously provide a bird's eye view of how the system and plant interface both with each other and the outside world. **Plant I/O Coupling**, in contrast, describes how this integration process appears to the *plant system*, a point of view shift that considers how, irrespective of the eventual goals of the artifact or designer, the plant is induced to express some detectable outcome. Given this definition, we observe that proxy integrated systems tend to focus specifically on input coupling with plants; while an artifact's hardware might tap into a plant's sensitivity to certain stimuli, it will not make use of any of the plant's output capabilities, as the triggered response is typically the end-all be-all of the design. In contrast, only directly integrated (embedded or augmented) systems employ any sort of *bidirectional* I/O coupling: setups in which the plant's natural output feeds back into the functional logic of the prototype.

As cataloged in Figure 4, past works leverage a subset of known plant sensory capabilities as input stimuli. But, while many prototypes often track the ensuing plant response as biopotential change (not pictured), to be translated into electronic signal fluctuations for interpretation and expression by familiar computing technologies, here we focus on cataloging the range of plant-specific material and physical outputs with immediate applicability to HCI. Though science has yet to fully grasp the diverse sensory capabilities of the plant kingdom (let alone its intelligent potential for collaboration), it helps to have a general grasp of what facilities are available to researchers. Owing to the fact that plant sensing in and of itself could be the subject of whole books [22, 41, 141], we will not attempt to give more than a cursory overview.

On the whole, the most widely-applied stimuli include light, moisture, sound, gravity, touch, vibration, and chemical presence. This spread of inputs is made relevant due to plant tropisms—biological phenomena in which certain plants grow towards or away from certain stimuli, often leaving a trail of evidence in the form of physical shape or temporal change; at times, a plant's acknowledgement of such stimuli can also be detected as a change in electric biopotential. For instance, thigmotropism refers to plant growth in response to touch; beanstalks naturally display this behavior in the form of spiraling tendrils which coil around objects upon contact. Zhou et al. [149] explored this aspect, in conjunction with gravitropism, by fabricating a series of 3D-printed scaffolds to manipulate the growth of oat roots into the shape of vases. Variation in environmental conditions, such as an increase in humidity—a phenomenon that Yao et al. [147] document heavily in their work—is yet another lever HCI designers can pull. An example of a lesser-explored input mechanism is sensitivity to airborne volatile organic compounds, which plants (and animals) use to send and receive information about, among other things, environmental conditions and stress levels [41, 132, 142]. While researchers in plant engineering and agriculture have probed into the space—mostly for plant monitoring and agricultural applications [84, 127]—airborne compound interaction has yet to be explored in the HCI community, likely owing to technological access limitations.

The space of possible outputs (by which we mean detectable plant-system responses) are a similarly complex and continuously-developing area. Heinrich et al. [55] provide a detailed catalog of mechanical and movement-based plant responses within the context of architecture. One popularly studied reaction includes visible changes in developmental growth, such as directional variation. English ivy, for instance, varies its growth trajectory in response to touch, while timelapse photography of the parasitic Dodder Vine shows it "sniffing" between various nearby plants to determine the most suitable host on which to feed [90]. Real-time movements, such as the near-instantaneous reactions of the Mimosa pudica [75, 135] or Venus flytrap [134], might be the most mainstream and

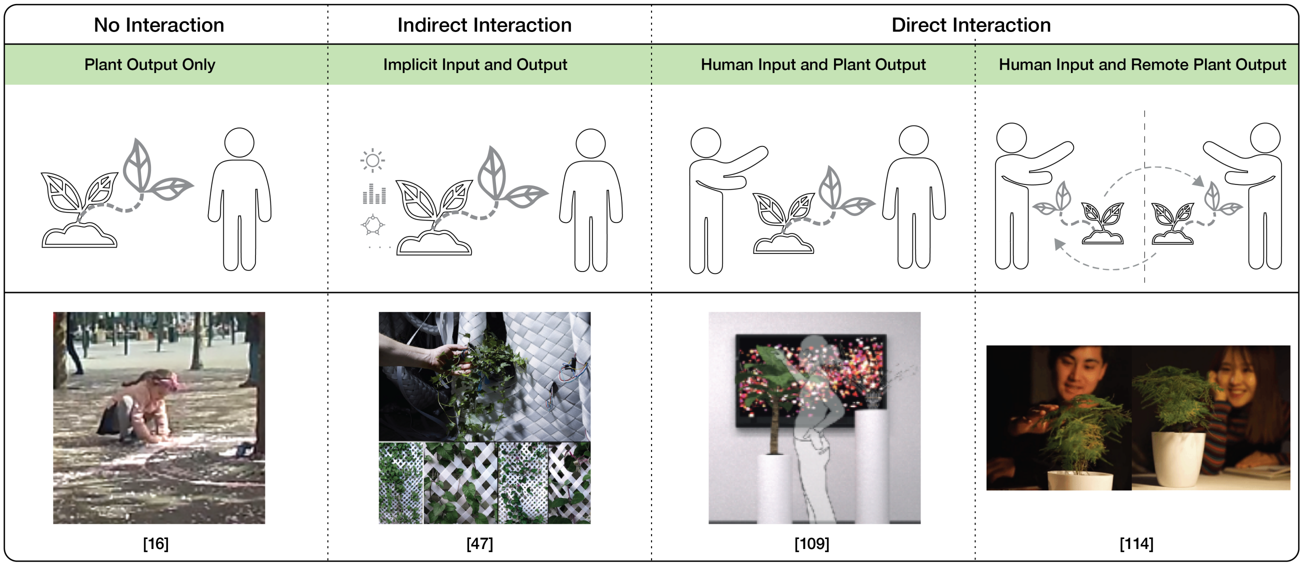


Figure 5: Interaction modalities employed by HPI projects can be generalized into three broad categories: No interaction (Plant-Computer Interaction, Beauty, and Dissemination [16]), indirect interaction (Flora Robotica [47]), and direct interaction. Direct interaction can either involve 1) human input and plant output (Botanicus Interacticus [109]) or 2) human input and remote plant output (Cyborg Botany [114]).

popularly-investigated plant responses, but output capabilities are not limited to the purely mechanical. Other possibilities include the release of chemicals, and color or intentional shape change (e.g., the *Boquila trifoliolata* vine mimics the leaves of the shrub on which it climbs [54]). In HCI, color change is often harnessed as a signaling or display mechanism [38, 113], and has opened up an entire area of exploration concerned with plant-based information displays [4, 15, 42, 49, 69, 74].

5.1 Interaction Modalities

The I/O coupling methods (plant input and output pairings) described above provide useful context for researchers and designers striving to define and implement the exchange between an HPI prototype and the plant system it contains. In contrast to Plant I/O Coupling, we use **Interaction Modality** to describe the opposite perspective of how *human users* engage with the plant system. We build upon an existing interaction framework [110] presented by Rasmussen et al. to describe three distinct categories of interaction modalities employed by past HPI projects: no interaction, indirect interaction, and direct interaction.

No interaction refers to scenarios where only the plant output is used to interact with the prototype or system. Here, input is not explicitly induced by any means of the designer; rather, it is left to the natural forces of nature and the surrounding environment in which the artifact is deployed. Enthusiastic bystander engagement with freshly-bloomed cherry blossoms in Japan, as highlighted by Aspling et al. [16], is an example of such a scenario (in this case, the artifact of interest is the cherry blossom tree itself). **Indirect interaction**, on the other hand, refers to scenarios where intentionally-induced changes (e.g., to stimuli like light, sound, chemicals, etc.) in the ambient environment provide a form of input, triggering a plant output with which a human user engages directly. For example, Infotropism [57] uses implicit input in the form of data about peoples' usage of recycling and trash containers to manipulate light, and thus the direction of plant growth; the goal is to bring human attention to social issues (in this case, sustainability and the circular economy) and thus encourage behavior change. Flora Robotica [47], another indirect interaction project, uses robots to guide plants into desired architectural forms for humans to enjoy. The researchers used a combination of light, hormones and far-red light to stimulate and influence the growth of various plant species. Lastly, **direct interaction** pertains to scenarios where human user(s) directly provide input to the plant (e.g., through touch, gestures, voice, etc.) and utilize the output either as a co-located entity in the same physical location as in "Growth, Change and Decay" [120], or as a remote, networked entity (illustrated by the bidirectional human-plant-plant-human communication envisioned by Cyborg Botany [114]).

Evidently, understanding the sensory and reactive capabilities of plants is valuable for outlining an entirely new toolbox of functional attributes HCI practitioners can leverage. One might even say that plant I/O coupling elements may be treated as individual "parts" in the design of an HPI system, as API calls are in software, or mechanical and electrical parts in physical assembly. Here, we identified that at the "macro" level, HPI prototypes typically fall into one of four types of interaction modalities. Of the works reviewed, indirect interaction and direct interaction (specifically, that of human input and plant output) were the most prevalent, as systems that employ no interaction are either contingent upon the capabilities of bioengineering and materials science or extremely hands-off, almost falling into the realm of pure observation or nature awareness. High-level system output typically takes the form of familiar human-detectable stimuli (e.g., light, color, sound, pixels on a screen), while the input, depending on interaction modality, may be a known plant stimulus. At the "micro" level, within each modality, input and output between the plant and any other technologies depend upon the inherent capabilities of the organism used. In mapping common plant system characteristics employed as input and output modalities, and examining their relationship to human interaction, we have addressed RQ2. Now, let us zoom out and consider the possible motives one might have for creating such a system at all—a factor that greatly determines subsequent design and implementation choices.

6 APPLICATION CONTEXT

Application Context refers to the underlying motive for an artifact's design—what change the work is meant to affect, the intention behind the system's creation, the social or societal context in which it is meant to thrive. Some are notably more human-centered than others. *Human health and wellness* applications are one of the most popular incentives for turning to plants as materials, as a growing body of research [130, 140] points to periodic and prolonged exposure to nature as beneficial for mental health and general wellbeing. The Pet Plant [94] is just one of several projects [14, 31, 61, 116] that investigates the efficacy of an "interactive 'pet' house plant" for providing emotional support and a sense of connection to vulnerable populations (e.g., the elderly). Another popular application is *sustainable product design* and work aimed at contributing to the circular economy. Such work often investigates the efficacy and feasibility of leveraging plants as fabrication materials [149] or substitute components of more familiar technologies such as conductive wires [13], information displays [42, 69], space lighting [44] or data storage centers [7]. Plants are a natural choice here, owing to their inherently biocompatible and biodegradable natures. Separately, much of the work from fields outside of HCI also come with motives of unlocking better *agricultural techniques* [18] or creating *city infrastructure or architectural formations*. Janni et al.'s work [62] on leveraging "bioristors" (organic electrochemical transistors) to sense ion concentration variation in tomato plants aims to enable the detection of drought stress in crops. Similarly, Wahby et al.'s experiments [136] around leveraging robotics to autonomously coax plants into desired shapes and patterns were conducted from motives of sustainable construction. From a philosophical perspective, it should be acknowledged that such application areas do not necessitate that the human-plant interaction design be mutualistic or symbiotic in any way.

That said, there also exists a body of work that seeks to decentralize humans in the interaction ecosystem. Such projects often fall into two main categories. The first includes those focused on cultivating *interspecies empathy*, and often stem from desires to increase human understanding or awareness of non-human organisms and

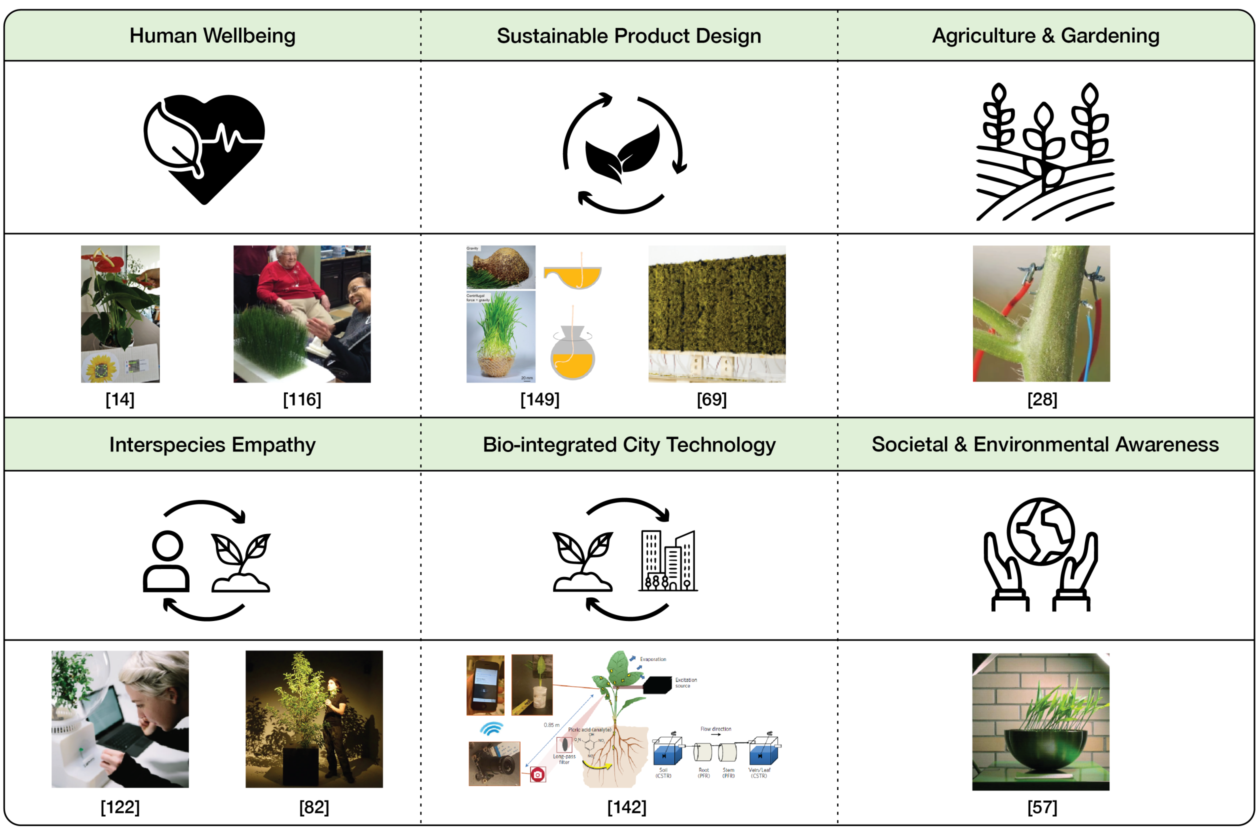


Figure 6: Common Application Contexts for HPI projects include human wellbeing (Multi-sensory EmotiPlant [14], Touchology [116]), sustainable product design (Digital Biofabrication [149], MOSS-xels [69]), agriculture and gardening (An in vivo biosensing, biomimetic electrochemical transistor [28]), interspecies empathy (Project Florence [122], Phonofolium [82]), bio-integrated city technology (Nitroaromatic Detection and Infrared Communication [142]), and societal and environmental awareness (Infotropism [57]).

ways of "being." This practice, which has been called organism-centered design [102], takes the view of treating non-humans as collaborators and partners in the creation of a work. Traditional computing technologies may be used to guide plant growth in a way that results in a collaborative human-plant artifact [47, 55] or, in the case of explorations like Project Florence [122, 126], to "translate" a plant's experiences into a human-comprehensible form (a stab at bidirectional human-plant communication). Others take a less on-the-nose approach and instead, strive to engineer human-plant interactions that inherently engender closeness to and curiosity about nature. Sound is a popular medium here. PlantWave [8] is a consumer product that allows users to attach electrodes to any live vegetal subject and enjoy a resulting selection of plant-generated music. Using a similar method, Wright et al. [143] digitally augment plants with gestural controls and mixed reality to explore co-creation with organic materials. ListenTree [108] brings the interaction to comparably wilder spaces and transforms public trees into living speakers; humans may listen to curated audio by laying their heads against the tree trunks. These are just a handful of many other art and design works that sonify [40, 81, 82, 93, 143] or otherwise propose making living vegetation interactive [71] to encourage contemplation on interspecies relationships.

The second category pertains to work focused on increasing human *awareness or understanding of pertinent social and ecological issues*; these are often cross-labeled "empathetic living media" or "empathetic biological media." Regardless, this subset of research strives to harness the living quality of organism-based media (e.g., microbes, fungi, vegetal subjects) to induce human empathy and activism by bringing attention to meaningful data. For example, Infotropism [57] uses a plant as a living information display to raise awareness of trash and recycling usage, while Bio-Fi manipulates a plant's living environment in response to changes in the stock market [34].

Evidently, the application context of an artifact dictates its setting, and the how and why of its interaction modality. By mapping the most common HPI design motives to human wellbeing, sustainable product design, agriculture/gardening, interspecies empathy, bio-integrated city technology, and societal/environmental awareness, we have explored RQ3. Notably, the underlying design motive strongly dictates how "organic" or "plant-like" [58] a design must be. In many ways, the application context is the root of the design, determining the chosen paradigm and subsequent technical approach. Will the work be placed in the literal wild? Should the work strive to be indistinguishable from its surrounding environment? Is it important that non-human entities interact with and are attracted to the object? And if so, how can this be accomplished?

7 PLANT INTERFACING AND MANIPULATION TECHNIQUES

Concrete approaches for implementing HPI projects tend to fall into one of five categories (although projects can certainly leverage more than one), two of which are technically feasible but currently absent from the HPI canon of work (see Figure 7). *Plant biomechanics* approaches often involve traditional gardening or folk wisdom related to working with plant systems, and can be as simple as tree staking [128] or leveraging common practical knowledge (e.g., that sunflowers turn to face the sun throughout the day), or as nuanced as indigenous wisdom of the Three Sisters—corn, beans, and squash—which Native Americans have understood to complement each other in agricultural contexts for centuries [68]. Next, *traditional computing*, which encompasses IoT technologies, software, and embedded computing elements like silicon-based sensing, is by far the most popular approach. One example is InfoPlant [49], a prototype of an ambient plant interface that uses a variety of standard electronic prototyping hardware to functionalize a typical houseplant. Among these components are Arduino-controlled fans to induce leaf rustling, servos for pulling strings tied to the plant's stems (to change its posture), LEDs, speakers, and a variety of off-the-shelf sensors. Similarly, Tanaka et al.'s toolkit for botanical computing [125] consists solely of elements commonly employed in the IoT space. In contrast, we define technical approaches that fall under *chemistry* as those that leverage chemical reactions. Babbage Cabbage [38] and BioMedia for Entertainment [113], for instance, rely on pH-induced color changes in living cabbage plants to generate meaningful variations in hue. A toolbox of such pH-reactive materials has been thoroughly documented by Kan et al. [65].

The last two technical categories, which result in system architectures that fall under the *augmented-direct* interaction paradigm presented earlier, are ripe for HPI exploration, but have not commonly been harnessed within the HCI community. *Materials science* methods include technologies like injected materials, which researchers in bio-electronics have been investigating for a good while [118, 119]. Cyborg Botany [114] is an example of an HCI project which uses the chemical polymer PEDOT:PSS to grow conductive "wires" inside a rose stem. Adamatzky [13], in contrast, takes a different approach regarding plant wires, by using lettuce seedlings as literal electrical wires in and of themselves; the objective is to probe into the feasibility of self-growing wetware circuits. Other materials science techniques include material deposition (e.g., hydroprinted electronic wearables for monitoring plant health [63]) and nanomaterials. Nanotechnology has particularly high potential for HPI work because of its ability to infiltrate porous plant membranes and grant plant-based interfaces the ability to detect and interact with desired stimuli without needing to use heavy-handed techniques to directly modify the plants themselves. In their work on nanobiotechnology approaches for engineering smart plant sensors, Giraldo et al. [43] illustrate the range of technical approaches and methods available to researchers. One promising example, Single-Walled Carbon Nanotubes (SWCNTs), offers the ability to interface with traditional computing technologies and has been of particular interest to those investigating in-vivo plant sensing within agriculture and botany. The application of SWCNTs has been shown to enable IR-detectable fluorescence in tomato plants and relaying the ensuing data to an Android app [142]. Going one step further, *synthetic biology* is notable because of its growing accessibility and ability to enable the direct modification of organisms. While still an emerging area in HCI and most often used where microbial subjects are concerned, synthetic biology promises great potential for HPI. Its invisible nature makes it suitable for projects which emphasize seamless integration with the environment. Ambient lighting via plant luminescence, for instance, is an oft-proposed vision of a way in which plants may be harnessed as aesthetic, subtle, and sustainable architectural fixtures [35]. To that end, recent research has

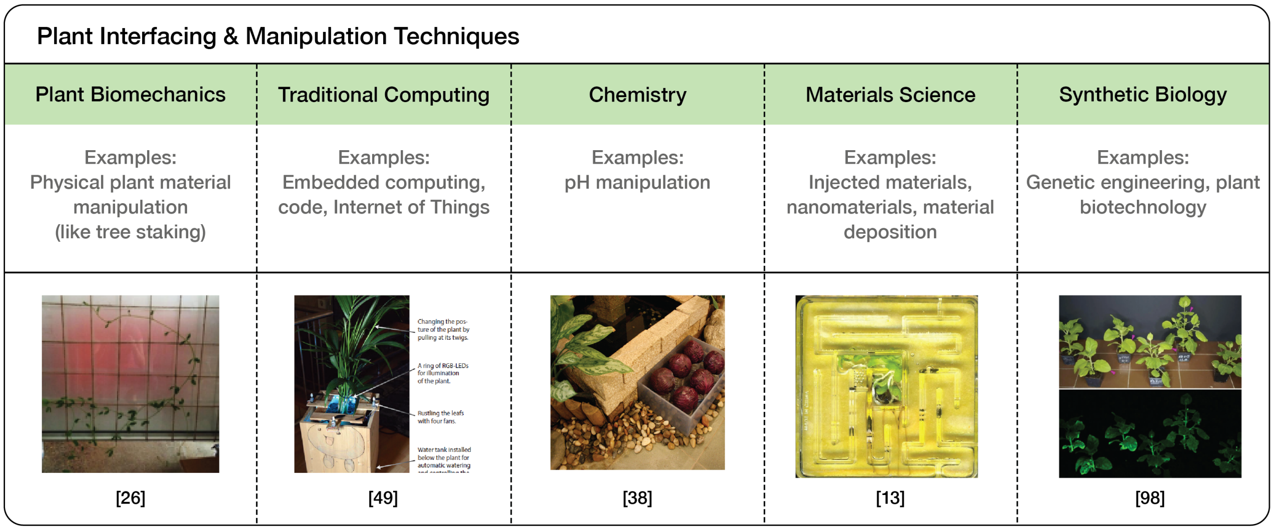


Figure 7: Previously employed interfacing and manipulation techniques in HPI prototypes include plant biomechanics (Biogotchi [26]), traditional computing (InfoPlant [49]), chemical manipulation (Babbage Cabbage [38]), materials science processes (Towards Plant Wires [13]), and synthetic biology (Plants with genetically encoded autoluminescence [98]).

demonstrated the ability to engineer bioluminescent plants [98] with built-in toggle "switches" [78]. In a similar vein, the rise of electrosynbiotics means that researchers are now demonstrating ways to generate power from trees [88] and the motion of dripping water on plant leaves [145]. Other exciting experimental projects like Grow Your Own Cloud [7] have probed into the feasibility and implications of using DNA to transform plants into data storage vessels.

Having laid out the HPI designer's toolbox of functional elements (and thus having contended with RQ4) it is clear that lesser-employed techniques like materials science and synthetic biology hold great promise for plant-integrated systems. A caveat, however, is that the emerging and somewhat niche nature of these technologies make them difficult to learn, obtain, and apply. This makes it difficult for HPI practitioners to understand or predict the potential impact an artifact may have in the wild—a concern which leads us to considerations of scale.

8 SCALE

Scale refers to an artifact's intended level of deployment. How broadly accessible is the artifact? What kinds of organisms are expected to engage with it or participate in the designed interaction? How much of the surrounding environment will be affected by the artifact? We think of scale as occurring at several levels; like a Russian nesting doll, the landscape of technologically-mediated human interaction with the plant kingdom encompasses scopes as concentrated as species-internal, to those as broad as the ecosystem itself. The concentric imagery here (see Figure 8) further helps convey that an interaction at one level may sometimes trickle outward to every subsequent level, though this does not apply to every case.

EmotiPlant [14] is one example of an artifact designed for isolated Human-Plant Interaction. Consisting of a potted plant, combined with a multitude of environmental sensors (soil moisture, temperature, photoresistor), the configuration is constructed to communicate when the plant needs water and to emote (via an LED matrix) when an interacting human touches the plant. In contrast, Wong et al.'s work [142] on nitroaromatic detection in plants is a more concrete example of an interaction that affects both the levels of plant-human and plant-environment (a level which encompasses not just humans and plants, but the natural elements and other non-plant species). The researchers infused living spinach plants with near-infrared fluorescent nanosensors, resulting in a configuration that both detects changes in fluorescence when groundwater contaminants are present and sends the data to nearby smartphone devices. Such a design, which is intended for large-scale deployment in the wild, concretely falls under the rings of plant-environment and plant-human (because of the smartphone integration). This configuration may also conceivably include plant-plant interaction; while no apparent communication or information exchange between individual spinach plants is worked into the design, one might nevertheless argue that plant-plant is implicit here, since vegetation in close proximity naturally exchange nutrients and chemicals. Indeed, the authors note that this "nanobionic approach…opens the door to the use of wild-type plants for infrared communications in wide areas, and real-time monitoring of environments such as cities, crop fields, high-security facilities, and homes." A more straight-forward illustration of plant-plant interaction is the "Grafted Illumination" example given by the authors of I/O Plant [72]. In this concept, trees are instrumented with multiple sensors and programmed to light up in response to significant changes. Affected trees may propagate this information to their neighbors, resulting in a chain reaction of light.

How deeply, then, have past researchers investigated the deployment of HPI prototypes at various scales of interaction (RQ5)? Simply put, the vast majority of the literature reviewed centers on singular human-plant interaction; this is because most projects are implemented and tested in a lab setting, focus on individual wellness applications for indoor settings, or act as isolated installations.

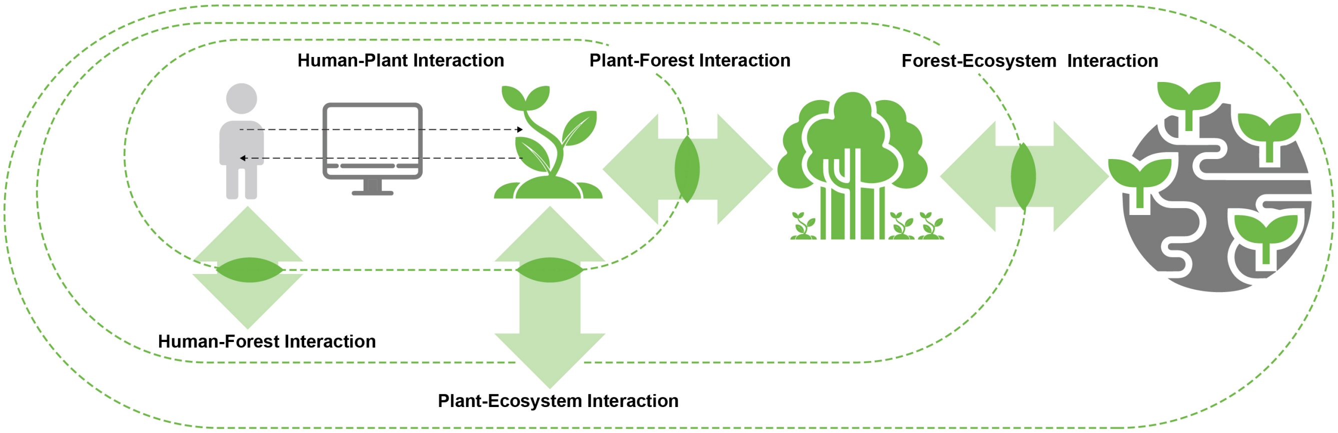


Figure 8: Scale of HPI prototype deployment and levels of interaction between plants, humans, and the broader environment

Plant-Forest Interaction is implied by proposals like Goumopoulos et al.'s PLANTS System [46], which presents a system architecture for enabling a distributed network of plants and hardware that allows for bidirectional communication between any node in the network. However, such instances have yet to be implemented in practice. Examples of single-plant-to-ecosystem deployments are more common. ListenTree [108] illustrates this by way of its being a set of individual trees that each allow multispecies users to interact and hear certain sounds; while any number of users may interact with a single tree, the trees themselves are not designed to interact with each other. The plant-ecosystem level of Scale is also highly relevant to research concerning crop monitoring in agriculture, often surfacing as a common area of investigation. But, as illustrated in Kim et al.'s exploration of vapor-deposited polymer plant tattoos for monitoring ozone damage [67], most such prototypes remain tied to the lab and have not yet been deployed in practice. Additionally, very few examples of plant-forest interaction exist in the HCI canon, possibly owing to the technical difficulties of achieving and controlling communication between multiple nodes of a distributed network.

Future opportunities for HPI research, then, naturally include experimenting with and understanding the effects of deploying plant-integrated technology in uncontrolled settings like public nature reserves, and examining the feasibility of creating networks of plants connected by way of various communication channels (e.g., in which information transfer is enabled by traditional computing or the exchange of airborne chemicals). While not explicitly a work within HCI, the indigenous root bridges of Meghalaya [146] are an especially compelling case study of how such work might manifest in the wild. Separately, we also observed that most HPI artifacts intended for isolated human-plant interaction are short-lived affairs, not often intended for engagement over long periods of time. Architectural projects involving the shaping of living structures [2, 89] tend to be the sole exception here. Other intriguing avenues of exploration include "heirloom" HPI artifacts and conducting diary studies with instrumented plants intended for indoor or health contexts.

9 DISCUSSION AND OPEN QUESTIONS

In this work, we reviewed 71 papers on plant-integrated HCI projects in order to understand the lay of the land and gain insights into open areas of exploration pertaining to our first five research questions. We determined that the system architecture of HPI works can be generalized into four major categories: indirect integration, proxy integration, embedded direct integration, and augmented direct integration; and synthesized the spread of common input and output formats into plant I/O coupling approaches and their usage in determining interaction modalities. We analyzed design motives in HPI by identifying six main application contexts, and determined that technical approaches for interfacing with and manipulating plants often fall into the buckets of plant biomechanics, traditional computing, chemistry, materials science, and synthetic biology. Finally, we studied the various scales at which HPI projects have historically been deployed, and identified plant-forest interaction as the least-explored area. Thus, through the five themes presented in our review, we answer our first five research questions. In this section, we address our final research question (RQ6) by illustrating how an exploration of past patterns and trends can help generate a systematic blueprint for approaching the space of HPI, and present opportunities and open questions for future exploration.

As a whole, the five themes identified in this paper form a framework (see Figure 9) that describes the range of technical and design considerations researchers must contend with when formulating a prototype for HPI. This is best illustrated with an example. A researcher wanting to create an artifact for the *application context* of encouraging interspecies empathy might first consider the *scale* at which the intended product will be tested or deployed. Perhaps the artifact is bound for single human use in a home. Or maybe, in deference to Blevis' [20] SHCI guideline of decoupling ownership and identity, it will be integrated into the ecosystem as part of a local nature preserve to optimize for public accessibility. From these constraints, the researcher might then begin to formulate a concrete implementation plan for their artifact and consider factors like what plant species they will use, what its unique traits are, and what technological approaches they will leverage to *interface with or manipulate* the plant system. During this stage, the researcher builds a high-level vision for how their overall system will be *architected.*

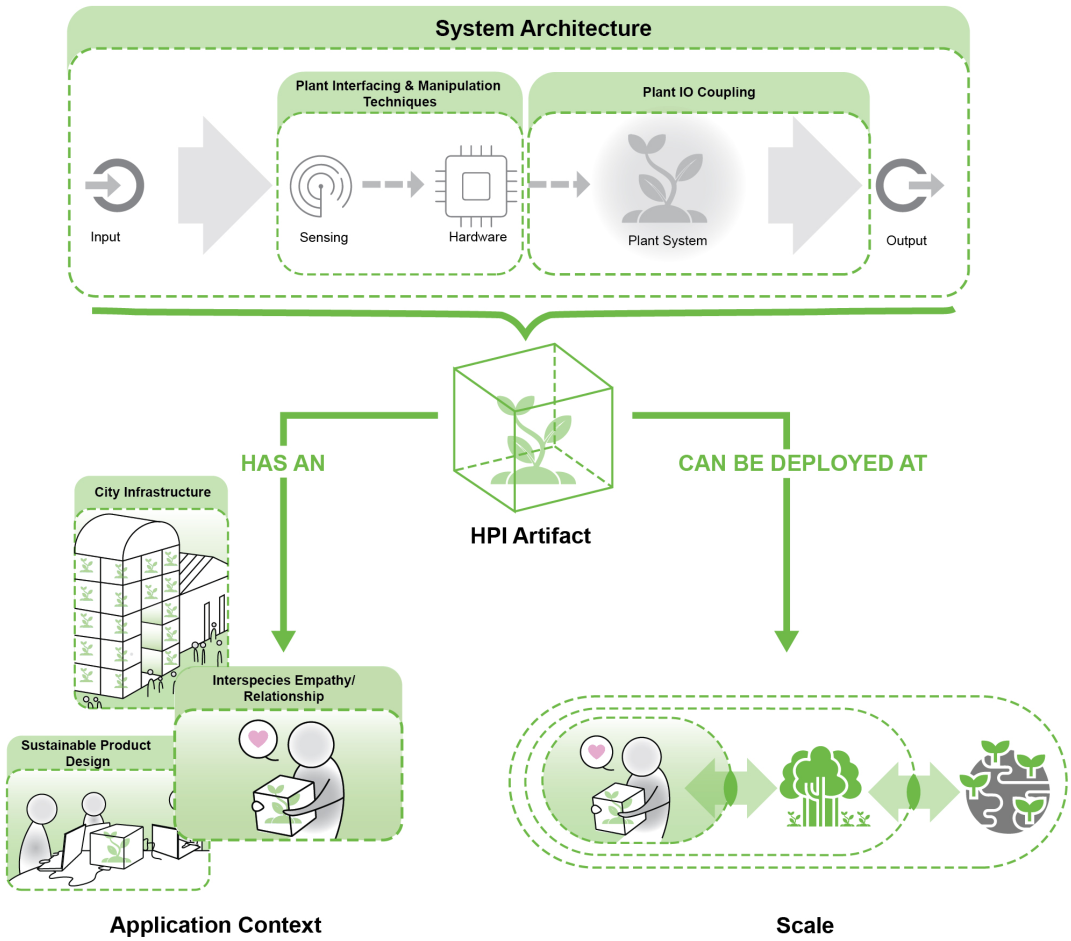


Figure 9: Design framework for future plant-integrated projects that leverages relationships between HPI System Architecture, Plant I/O Coupling, Manipulation Techniques, Application Contexts, and Scale (of deployment).

For example, the desire to elicit empathy may drive the researcher to select manipulation and interfacing techniques that are particularly compatible with the implicit design intent of non-malfeasance towards the non-human. Further, a designer striving to account for the environmental impact of their prototype might either opt for an ambient technology approach to minimize disruption to local residents (both human and non-human) or consider bio-compatible, bio-integrated implementation techniques like plant engineering or injectable conductive polymers to functionalize their vision. This technical decision subsequently determines the overall *plant I/O coupling* design of the prototype, as it affects the availability of certain data or interfaceable output from the plant partner. With these considerations in mind, the resulting prototype might feature the following *augmented direct integration* scenario: A person takes a walk in their local municipal nature preserve, wanting to forest bathe for a while. They round a bend to see a cluster of children carving into its tender bark, taking selfies with their doodles and plucking its flowers for aesthetic effect. Indignant, the person draws closer and sees a compostable tag high on the trunk: "Place palm here." The person does so. Immediately, all smartphones within a five-foot radius of the sapling become live, infrared windows to the surrounding environment. The selfie-snappers, fixed to their phone screens, gasp to see what appears to be a green mist emanating from the tree's damaged areas, spreading to other nearby vegetation. Annotations onscreen helpfully supply that they are watching a live feed of IR-detectable, airborne chemical communication from the sapling, and that the green mist is methyl jasmonate—a pheromone released by plants when in distress. As illustrated, by using our framework to approach the prototyping process, a researcher is not just given the tools to consider their design from a functional perspective, but compelled to consider its social, sustainability, and interspecies impact as well.

Our synthesis of existing HPI projects into an overarching framework allows HCI researchers and designers interested in building with live vegetal subjects to better comprehend the space of existing cross-disciplinary research, the range of toolsets and technologies at their disposal, and structured methods for conceptualizing and executing such work in practice. However, this review would be remiss without a discussion of the gaps, opportunities, and open questions relevant to future examination of this space. Here, we highlight some ethical and philosophical considerations HCI practitioners must grapple with when designing with living plants, pose questions about common patterns that emerge when faced with the current body of work, and posit a selection of less-explored avenues we believe are important for the future of de-anthropocentric design.

9.1 Why this plant?

As exemplified through our catalog of HPI design paradigms and the space of application contexts, the reasons researchers choose to investigate HPI are diverse and varied. Each project has a different motive for selecting a vegetal subject as the most suited medium for the intended purpose, ranging from plant exposure being beneficial to wellbeing, to the simple fact that plants possess untapped technological potential as evolutionarily diverse organisms. However, few projects other than, perhaps, those involving species that react to stimuli with dramatic, human-detectable changes (e.g., "Venus flytrap," *Mimosa pudica*) articulate why a specific species is most suitable for the prototype being built. Rather, most works appear to generalize all vegetal species as a whole, or use common nursery plants (e.g., roses [114], tomato plants [142], anthurium andraeanum or "laceleaf" plants [122]), as opposed to intentionally seeking out a wider range of subjects. What about varieties that thrive in different biomes or mature to very small or large sizes (significant factors to consider when optimizing for artifact longevity or reuseability)? Given that vegetal species display specialized features unique to their environments, physical characteristics, and ways of living, neglecting to explore this diversity seems like a missed opportunity. HPI as a design space would certainly benefit from more researchers carefully considering the variation of plants at their disposal and motivating their decisions (possibly with the aid of botanists) through the acknowledgement of specific traits when discussing their approaches.

9.2 Justifying design decisions: Connecting plant agency, intention, and implementation

As multiple scholars have pointed out [37, 41], traditional views around plant subjects in Western philosophy and research have thus been largely anthropocentric. We use plants for purposes like food, medicine, and pleasure, and design experiences around them that, more often than not, focus on benefiting human users and treat plants as resources. In our review, we similarly found that the nature of the human-plant relationship in question and its implications are less discussed by authors, unless the project is expressly aimed at generating interspecies empathy. It is already an established practice in HCI to discuss ethical and social implications when designing interactions between humans and between humans and animals. Perhaps the HCI community should normalize considering the impact of designed interactions on plants and the larger ecosystems they inhabit as well. That is, do the authors strive to work with the plant as a collaborator or as a material? How much agency from the plant is desirable? How does this relate to the intended application, chosen technologies, and philosophical underpinning behind the project? Is there a desire to consider the plant's wellbeing and happiness in the relationship? If so, how and how is this quantified?

As our framework makes clear, the five themes of System Architecture, Plant I/O Coupling, Application Context, Interfacing and Manipulation Techniques, and Scale are interconnected. Deliberately beginning from a place of wanting to harness a plant's innate circadian rhythm, for instance, combined with the resources at the researcher's disposal might mean that an interfacing technique like embedded OECTs will bring the project closest to its objective. In another case, a researcher might establish that plant agency is important to them and that the use of inserted sensors to enable the reading of biosignals is more physically disruptive than they are comfortable with; thus, they might opt for the more hands-off proxy integrated approach or leverage bio-compatible and non-toxic augmented technologies that, as previously acknowledged, are more popularly employed in bioengineering or agriculture, and that are known to be harmless to plants. To that end, augmented system architectures present themselves as one of the most exciting opportunities for future research in HPI, with the potential to unleash a host of technically, ethically, and philosophically challenging conundrums positioned to change our relationship with ourselves, other organisms, and nature.

Our review also suggests that projects connected to an established view on plant agency on the outset, will find their implementation and design decisions dictated accordingly. If the artifact is not meant to approach the plant as a co-collaborator, for example, then the designer's choice of interfacing technology is not beholden to factors like environmental health or plant longevity. It follows that establishing a position on the matter before diving into execution will allow authors to more effectively work through where their prototypes stand along the five themes. We encourage researchers to consider more explicitly justifying their design choices around the chosen plant material and five HPI themes in future work. The HCI community may also benefit from working with botanists and agricultural and indigenous experts to create a resource clarifying how certain aspects of each theme relate to plant ethics (e.g., which plant interfacing technologies are more suited to design motives of interspecies empathy, and the pros and cons of each in relation to various types of human-plant relationships). Ideally, such a project would help researchers gauge alignment between their selected technical approach and their philosophical beliefs and aims.

9.3 Towards sustainable systems: Mutualism and integration with nature

In "Designing for Sustainability," Nathan Stegall writes that "the role of the designer in developing a sustainable society is not simply to create 'sustainable products,' but rather to envision products, processes, and services that encourage widespread sustainable behavior" [121]. As our themes of Plant I/O Coupling and Plant Interfacing and Manipulation Techniques make clear, the plant kingdom is home to a colorful array of species, each embedded in its own unique biome, with its own characteristic mechanical, sensory, material, and aesthetic properties. This specialization of species makes plants especially enticing as design partners; each already performs a special role in its home environment, whether it be structural support for sheltering the local flora and fauna, air cleaning, or as a provider of much-needed nutrients. In better understanding plants themselves—their capabilities, preferences, functional properties, and nuances—and disseminating that knowledge (through conversations, the frameworks proposed in this paper, and engaging other creators), we hope to paint a picture of a plausible future in which humans, through an understanding of and connection with nature, may tap into pre-existing systems in the wild and work with them to symbiotically achieve a desired end result. In striving to work with plants as unobtrusively as possible, then, HPI researchers inherently address Blevis' design principle of "using natural models," which the author clarifies as "making the world of the artificial more like the natural world with respect to sustainability" [20].

One classic example of such an approach includes the root bridges constructed by indigenous communities in Meghalaya [146]. The bridges are constructed by planting rubber fig trees in desired locations, applying bamboo scaffolding, and then monitoring and shaping their growth over the course of years (10-15 on average); it is a community-driven effort that requires respect for and understanding of the local flora and ecosystem in which they thrive—an act of engineering that is not just sustainable in and of itself, but that deeply embeds sustainability principles within the ethos of local cultures. The root bridges beautifully illustrate a setting in which technology and nature form a mutualistic partnership: Humans get a functional bridge, and the *Ficus elastica* get to ensure their continued survival. At the same time, this tradition of partnering with plants is not an isolated example; cultures around the globe have a long history of working with vegetation to create purely mechanical or agricultural outcomes.

What might it look like, then, to move beyond such practices and create new traditions? How might such a partnership come about when we consider current technologies? How might human-plant relationships flourish when innovations like modern sensing, biodesign theories, and synthetic biology are thrown into the mix? The frameworks proposed in this paper provide a starting point for researchers to think about how plants and emerging technologies might be leveraged in a way that aligns with the goals and objectives of the many complex systems and stakeholders often involved in such efforts. However, they are most effective when used not in isolation, but when paired with an understanding of more-than human [29] or posthumanist design theories—schools of thought that combine the human and nonhuman to consider other species, actors, and ways of being. Some examples include frameworks like actor-network theory, which perceives the world as networks of ever-shifting relationships between actors which may be equally human or nonhuman, and socialist-feminism discourse like that of Donna Haraway, who writes about intersections in social, design, and technological contexts [51, 52]. In her work, "Staying with the Trouble," which argues for remaining fully present during this age of environmental and social upheaval, Haraway urges readers to consider the concept of sympoiesis ("making-with"): "If it is true that neither biology nor philosophy any longer supports the notion of independent organisms in environments…then sympoiesis is the name of the game in spades" [53].

Let us return to Stegall's point about designing to induce sustainable behavior. One might argue that building technologies that leverage plants as functional components is inherently sustainable. Plants check all the boxes: They are part of nature, inherently compostable and biocompatible, and great for decarbonization. But it is not enough to simply build with living plants as material without considering what Laura Forlano describes as "the multiple agencies, dependencies, entanglements, and relations that make up our world" [39]. Suppose it were immediately feasible to create a completely plant-based power grid that, in the spirit of Peralta et al.'s Biophotovoltaic Moss Table [107], employs a specific species of moss to generate electricity. The common reaction might be to immediately allocate large swathes of land to cultivating this specific species of moss, and to import it all over the globe to share this new source of bio-based bliss. But perhaps it would be prudent to slow down a bit first—consider the matter from multiple angles. By many accounts, and certainly according to many standard SHCI principles, this hypothetical invention would certainly be a sustainable material creation. Yet, as Forlano writes, "considerations of the nonhuman…require new forms of expertise and open up new problems, questions, opportunities, and solutions for the field of design that it is not yet equipped for." For example: How might such a move impact local plants or insects? Would the designers be introducing a possibly invasive and/or hazardous species to the local ecosystem? And, what does the moss get out of this transaction (or are we simply "draining" them like batteries)? We challenge HCI researchers to consider such questions in their work and to explore what artifacts may result from remixing design guides like the one presented in this paper with various posthumanist design frameworks, in lieu of traditional human-centered design approaches. In this way, we might strive to transcend imitation or parasitism, and move towards respectful, longer-term partnerships with the untapped potential of nature.

9.4 Anthropomorphism versus empathy

As mentioned in our analysis of application contexts, a subset of projects focus on establishing interspecies empathy by conveying a plant's sense of being, aiming to nurture a new kind of relationship between human and nature. The vast majority of such works accomplish this by converting known plant-relevant environmental signals into forms of information that are relatable and understandable to humans (e.g., sound, socially-meaningful light patterns like smiley faces [27]). Given the complex and emerging nature of the task, it bears questioning: to what extent are classically human-centered methods of translation (e.g., the written word, in the case of Project Florence [122]) anthropomorphizing plants as opposed to conveying their true perceptual world? Could certain methods be undermining their proffered motives by inadvertently communicating an artificial, zoocentric construction of plant being? And if so, what alternative technical approaches and design decisions might help similar efforts remain true to reality? As Gagliano writes in *The Language of Plants*, "plants are still expected to exhibit animal-like qualities in order to be acknowledged as sensitive living organisms, rather than being appreciated in their own right and on their own terms" [41]. To be sure, the range of interspecies-centered projects surveyed in this work certainly supports this claim.

As yet, works focused on bridging interspecies relationships have yet to go beyond silicon-based sensors, and thus tend to employ the proxy integrated system architecture. It is possible that experimentation with a greater variety of technical approaches might allow such works to gradually phase out human and machine inference from HPI systems and help convey information directly "from the source." We encourage researchers active in this area to ponder methods of allowing humans to tap into sensations and signals in ways that are perhaps unintuitive to us, but closer to the non-human experience.

Separately, many such projects also remain in the realm of interactive art or bespoke thought pieces [64], leading to a lack of systematic evaluations assessing the true efficacy of such artifacts in bridging interspecies relations. Future researchers may find it valuable to reflect on methods for measuring and quantifying human-nature empathy and to consider running dedicated user studies on the efficacy of their artifacts.

10 CONCLUSION

In this review, we examined past work across HCI, with select projects in relevant fields like bioengineering, materials science, architecture, and agriculture, to uncover design patterns in Human-Plant Interaction and understand how the HCI community might move forward with such research in a way that considers human relationships with non-human species. We presented a framework for dissecting and approaching the execution of such prototypes, encouraging readers to think of HPI projects as reflecting one of four HPI Systems Architecture paradigms (indirect integration, proxy integration, embedded direct integration, and augmented direct integration), and spanning across the dimensions of Plant I/O Coupling, Plant Interfacing and Manipulation Techniques, Application Context, and Scale. We hope that in providing a systematic framework for plant-integrated technology and interaction design, we have made it easier for subsequent researchers to situate their projects within the context of the HPI space, understand the range of tools and techniques available to them, and consider the societal and interspecies implications of their research goals.

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