Guttation Sensor: Wearable Microfluidic Chip for Plant Condition Monitoring and Diagnosis

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Figure 1: The guttation sensors mounted to various plant leaves. From the large and thick *Monstera deliciosa* leaf (a), to thin and sharp grass leaf (d).

ABSTRACT

Plant life plays a critical role in the ecosystem. However, it is difficult for humans to perceive plants' reactions because the biopotential and biochemical responses are invisible to humans. Guttation droplets contain various chemicals which can reflect plant physiology and environmental conditions in real-time. Traditionally, these droplets are collected manually and analyzed in the lab with expensive instruments. Here, we introduce the Guttation Sensor, the first on-site and low-cost monitoring technology for guttation droplets. This innovative device employs a paper-based wearable microfluidic chip capable of collecting and conducting colorimetric detection of six chemicals. We discuss this technology's design and implementation, conduct evaluations on tomato plants, and envision how such a technology could enhance the human-plant relationship.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing**; • **Hardware** → *Sensor applications and deployments.*

KEYWORDS

plant, sensor, guttation, low-cost

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1 INTRODUCTION

Plants have significant ecological and social value. They serve as a primary source of food and oxygen for many organisms and are essential in regulating the global climate. Additionally, human activities like gardening, agriculture, horticulture, and landscaping rely heavily on plants. In recent years, the field of Human-Computer Interaction (HCI) has explored ways to create smart and interactive systems incorporating plants [21, 39]. Existing research leverages plants as sensing and display systems, utilizing peripheral sensors or introducing conductive organic polymers and biocompatible materials [21, 22, 36, 50]. Additionally, plants are explored as emotion-evoking entities and natural companions for educational and wellness purposes [4, 10, 38, 42]. The emerging focus on multispecies HCI has spurred research in developing symbiotic human-plant relationships, fostering empathy for non-human entities like plants and the environment [7, 18].

Meanwhile, wearable plant sensors are becoming increasingly popular as demand rises for monitoring plant health in smart homes, gardens, and farms, combating climate change, and improving plant-human coordination [24]. Many wearable sensors have been developed that can detect environmental stressors [16, 33], monitor plant growth [14, 52], and measure plant volatile organic compounds (VOC) [6, 25]. However, guttation, a unique plant physiological activity, has not been well explored. Guttation droplets are a common secretion of plants that contain various organic and inorganic chemicals that can be used to understand the plant's status and environmental conditions. While guttation droplets are traditionally collected manually and analyzed in the lab with expensive instruments [20, 34, 58], we introduce the Guttation Sensor, a low-cost, on-site sensing technology for guttation droplets (Fig. 1). The Guttation Sensor employs a paper-based microfluidic chip that can collect guttation droplets and perform colorimetric chemical detection. The detection result can be estimated with the naked eye or digitally. While fluids have been extensively investigated as an actuation medium for morphing interfaces [27–31], it is noteworthy that fluids, such as guttation, can also convey valuable information. This information holds potential for the development of interactive systems.

We briefly summarize our core contributions as following: 1) This is the first on-site technology that senses guttation droplets via a plant wearable device. We have shown that six types of chemicals can be sensed on a single paper-based microfluidic chip. Though the sensor is single-use, it is very low-cost [1]. 2) The sensor design is uniquely tailored to plant guttation sensing. The sensor is conformable, ultra-lightweight (~0.03 g), and requires a very small sample volume. 3) On-plant experiments are conducted to validate the sensor and primarily explore how we can leverage the sensor data to interpret plants' status and provide corresponding suggestions to humans. We hope the wearable plant sensor will become an enabling technology for researchers interested in human-plant

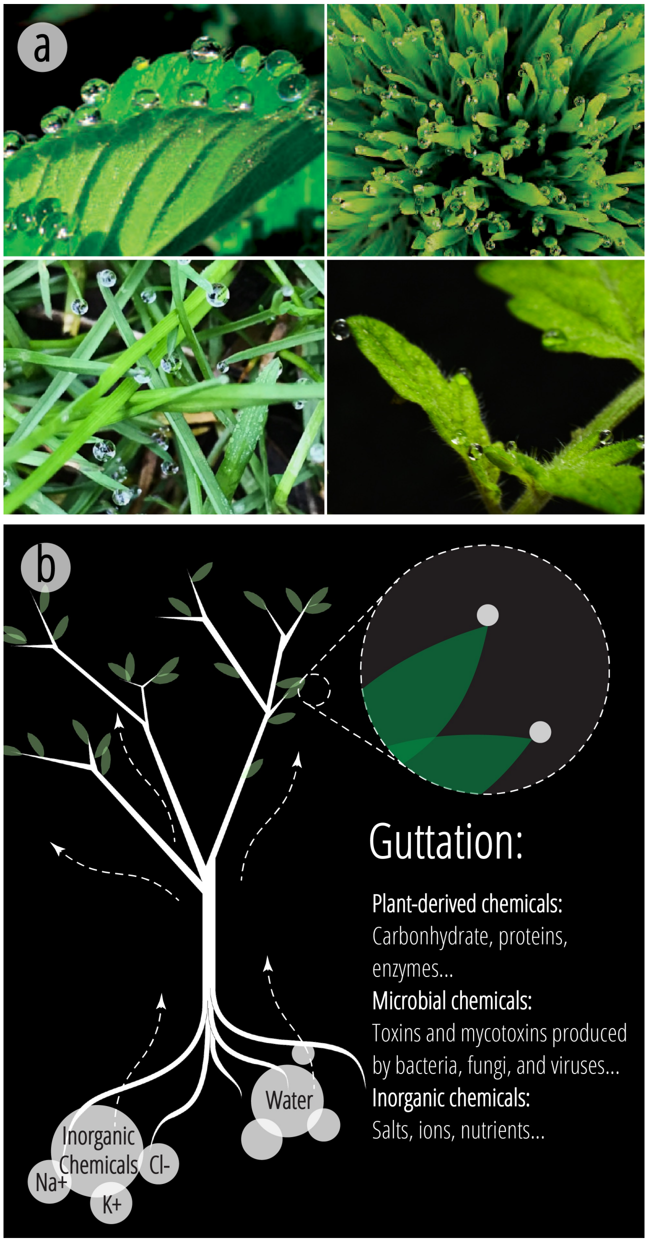

Figure 2: (a) Guttation in the form of droplets in different plant species: strawberry (source: Wikemedia), annual blugrass (source: Wikemedia), bentgrass (shot by author), tomato (shot by author). (b) Chemicals that can be found in plants' guttation droplets.

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[1] Calculated based on the US Amazon retail price of the material used, the cost of the sensor is around 50 cents. We also sent inquiries to suppliers and factories in Asia area. Based on their quotations, the cost can be reduced to less than 10 cents with mass production.

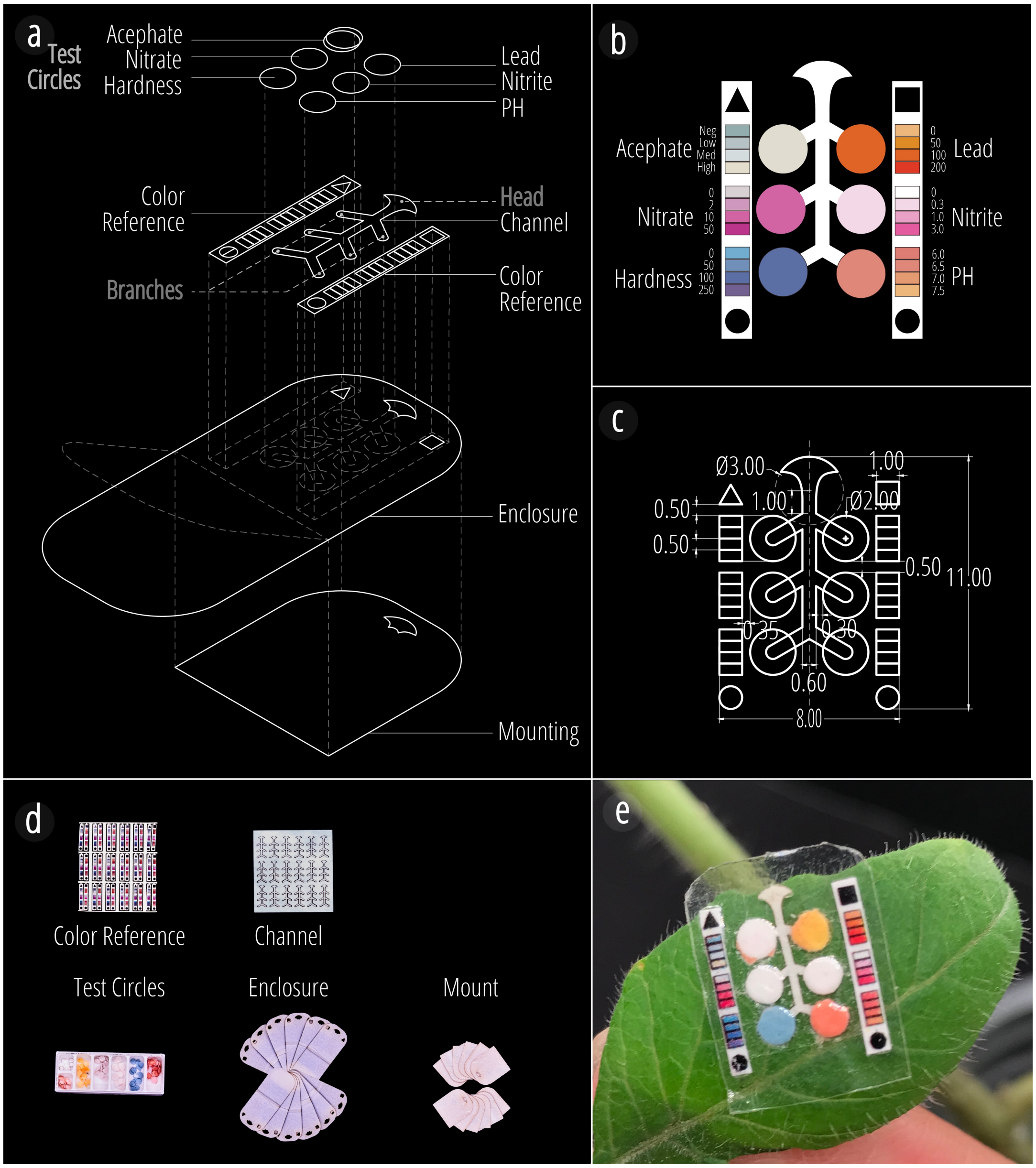

Figure 3: (a) Exploded axonometric diagram of the sensor. (b) Color reference. (c) Dimensions of the sensor (d) Components of the sensor, unite: mm. (e) Sensor implemented on the plant.

interaction, in various contexts such as plant status monitoring, soil condition monitoring, and augmented interactions among plants, humans, and other species (e.g., pollinators).

2 BACKGROUND KNOWLEDGE

At dawn, plant teardrops, or guttation, emerge as clear droplets secreted through leaves, a process common in various "plant" types, including angiosperms, gymnosperms, ferns, algae, and fungi [47]. Root pressure propels xylem and phloem sap through pores, aiding the plant in eliminating excess water and materials during periods of high soil moisture. Guttation differs from transpiration and dew, occurring when transpiration is low and compensating for water buildup. Transpiration decreases, and guttation increases in high humidity when vapor concentration outside the plant is elevated. Unlike guttation, which depends on the plant's health, dew forms at night due to atmospheric water vapor condensing on the leaf surface, with its composition dependent on atmospheric conditions [2, 46, 57].

Guttation is an important indicator of a plant's status. We chose guttation because it contains (Fig. 2.b): many inorganic compounds [8, 9, 13, 35], which directly reflect what the plant absorbs from the soil [44]; organic chemicals produced by the plant such as carbohydrates [47, 49], proteins [12, 32], and hormones [51]; and microbial chemicals, such as toxins and mycotoxins produced by bacteria, fungi, and viruses [11, 40, 62], which can be found in the early stage of infection.

Guttation, with its mix of inorganic and organic compounds, offers a snapshot of the plant's chemical environment, providing a non-invasive method to assess soil fertility and productivity. Analysis of guttation chemicals enables targeted responses to address plant deficiencies. Studying guttation goes beyond monitoring plant health; it serves as an indicator of the surrounding environment. Guttation plays a vital role in the plant's immune system, flushing out pathogens [47]. Research explores using guttation analysis to engineer crops beneficial to herbivores and resistant to pathogens [48]. Guttation's carbohydrate and protein content can serve as nutrient-rich food for insects [55], yet it may also carry harmful chemicals like neonicotinoid insecticides, impacting insects such as bees [53]. Understanding guttation composition is thus crucial for ecosystem well-being.

3 PLANT WEARABLE MICROFLUIDIC SENSOR ENABLED GUTTATION MONITORING

The colorimetric microfluidic guttation sensor is compact, lightweight, low-cost, and can adhere and conform to the leaf in a manner that captures and routes guttation droplets through the microchannels to the test circles. We construct the guttation sensor based on a paper microfluidic chip rather than a 3D channel microfluidic chip (e.g., Polydimethylsiloxane cast chip, 3D printed chip) because paper microfluidic chips can work purely on capillarity, while 3D channel microfluidic chips require extra pressure at the inlet [19, 23, 64]. Furthermore, to avoid back-pressure, all channels must be interfaced to an outlet when designing a 3D channel microfluidic chip. Condensed moisture may get into and pollute the chip through such a structure. Paper microfluidic chips do not require such outlets. Lastly, paper is very affordable and much easier to process and assemble rapidly [61].

3.1 Designing the Guttation Sensor

Overview. The guttation sensors comprise a multi layer stack of five components (Fig. 3). From bottom to top, they are: *The mounting* is a leaf-compatible double-sided adhesive layer with a sector shape opening for the guttation droplet collection; *The enclosure* is an ultra soft and thin one-sided waterproof adhesive with the same sector shape opening aligned with the opening in the mounting. In addition, it has a triangular cut and a rectangular cut to assist in locating the reference when assembling the sensor; *The reference* consists of two printer paper strips with colorimetric reference to help identify the chemical concentration and image processing markers at both ends; *The channel* is a piece of tree shaped Japanese paper with one sector shape inlet and six branches. It can absorb the guttation droplet with the sector head and carry the fluid to the end of each branch; *The test circles* are for colorimetric detection of different chemicals, such as lead, nitrite, PH, acephate, etc.

Design Optimization. We optimized the materials, geometry and function of the Guttation Sensor's design.

Materials. For the Mounting, we use 3M 468MP Adhesive Transfer Tape, which has the just right amount of stickiness for mounting the sensor and will not hurt the leaf when removing the sensor. The enclosure needs to be lightweight, conformable and can protect the inside components from hard surfaces. We choose a thin, soft, waterproof polyurethane (PU) film (Areza Medical, Transparent Adhesive Film Dressing) for the enclosure. The reference is printed on regular printing paper. The test circles are punched from off-the-shelf test strips.

As for the channel, we needed to find a paper material with good water absorption and minimal chromatography. Because chromatography will make solutes, especially large molecular weight solutes, fall behind the solution (in our case, water), accumulating and leading to inaccurate colorimetric test results. We selected three kinds of paper with high absorbency: Japanese paper (ONAO), chromatography paper (LOSTRONAUT, Grade-1), and filter paper (Eisco Labs, medium speed - 85 GSM, 10 micron pore size). We then carried out an experiment to test them. All three papers were cut into 5 mm x 30 mm strips and had nitrate test squares placed on one end. A sufficient and identical amount of nitrate salt solution was dropped simultaneously to the other end of the strips. The time for water and nitrate salt to reach the test square was recorded. All three papers have similar and very good absorbency, while the Japanese paper has the lowest chromatography property. Japanese paper is also more affordable than the other two kinds of paper, making it an even better choice.

Geometry. The geometry of the Guttation Sensor is illustrated in Fig. 3.c. Most of these parameters are established around the dimension of the test circle. The diameter of the test circle is 2 mm, which minimizes the sample volume requirement while not being too small to handle during manual sensor assembly. The channel has close to the minimum width that most laser cutters can properly handle and has a relatively larger sector shape area to increase the chance of successfully collecting guttation droplets. A 0.3 mm, 0.3 mm, and 0.5 mm safe distance between the channel and the test

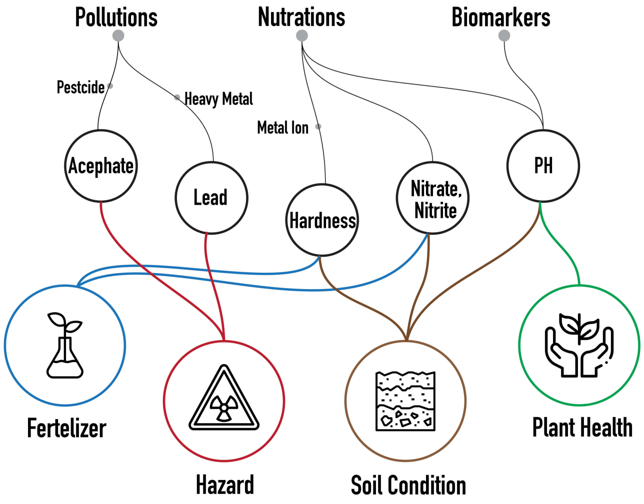

Figure 4: Chemicals the Guttation Sensor can detect and what environmental factor they are related to.

circle, between the reference and the test circle, and between the individual test circles are reserved respectively. The rectangle color reference patterns are grouped and aligned with the test circles. A guttation droplet's volume can vary. For the tomato plants we tested, the volume usually is above 0.3 ml, which is far more than enough for our compact sensor.

Function. Some functional aspects have already been discussed, e.g. the channel has a larger inlet to facilitate guttation drop collection. In this part, we will mainly discuss how we design the core functional component of the sensor: The colorimetric display. We select six chemicals to detect, with the following concerns and hypotheses (Fig. 4): *Acephate*, Pesticides pose a danger to the ecosystem. Thus, we select one kind of pesticide, acephate, to validate the sensor's capability of detecting pesticide residue. Acephate is an organophosphate systemic pesticide that is absorbed into plant tissues and sap where it is consumed by sap feeders [43]. *Lead*, Land contamination is another problem that devastates our ecosystems [5]. We chose lead to see how soil lead pollution may be reflected in guttation droplets. *Nitrate and nitrite*, Nitrogen fertilizer is one of the most widely used in modern agricultural practices, and it often comes as nitrate salt [60]. Monitoring their levels can help us understand if the plant is lacking nitrogen or if is overdosed. *pH*, guttation pH level has been shown to be highly related to plant heath [56]. *Hardness*, the hardness level is an indicator of the necessary calcium and magnesium ion concentrations [41]. We purchased many different kinds of test strips, prepared some standard solutions of the aforementioned chemicals, tested the chemicals with the strips, and selected the most accurate and sensitive ones. The reference color is extracted from the reference provided by the aforementioned product. The pH reference is selected based on the fact that most plant sap is weakly acidic when healthy. The hardness reference is decided by making sure it can cover soft, medium and hard. The acephate test strip only comes with three levels that it detects - negative, low and high. To enable more precise acephate tracking, we added another medium level color falling between low and high.

3.2 Making the Guttation Sensor

The channel array, reference array, mounting, and enclosure were modeled using AutoCAD and Illustrator and then cut with a laser cutter. To prevent laser-induced high temperatures from affecting the reaction ingredients, the test circles were mechanically punched out. The sensor assembly procedure is illustrated in Fig. 5 and consists of the following steps: a) Take one channel from the array; b) Remove half of the protective cover of the enclosure and mount the channel, ensuring that the sector-shaped parts are properly aligned; c) Mount the reference strips to the enclosure, aligning them with the triangular and rectangular holes on the enclosure; d) Arrange the test circles in the correct order, noting that acephate requires two overlapping test circles; e) Remove the other half of the protective cover and fold the enclosure; f) Remove one of the rigid support covers of the enclosure on the other side, and attach it to the mounting layer; g) Remove the other rigid support cover from the enclosure; h) Remove the rest of the protective cover from the mounting layer before attaching the sensor to the plant.

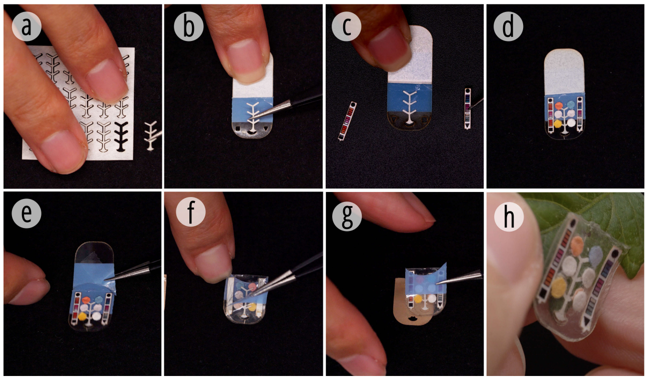

Figure 5: The assembling procedure of the guttation sensor

4 GUTTATION ANALYSIS USING THE SENSOR

We did a series of experiments with the Guttation Sensor on one-month old tomato plants in a grow tent. The artificial sunlight was set to 8 hours at 25000 lux, the temperature was set at 26°C, and Humidity level was controlled at 60%. To precisely control the concentration of the chemicals of interest, we transferred the tomato plants to hydroponic systems with 1L filtered water, and let them sit for three days. We then deployed the Guttation Sensor and applied chemicals of interest with various concentrations to the water. The next day, the plants were kept at 90% humidity, 26°C for 3 hours in the early morning before the artificial sunlight cycle in order to induce guttation. The exeption to this was acephate, which was monitored continuously for 14 days.

For each chemical, three sensors were deployed on three plants separately at different concentration levels. Data was collected by taking photos and comparing the RGB values of the test circles with the reference values. Nitrate, nitrite, and hardness levels were controlled via Greenway Biotech calcium nitrate fertilizer. Fertilizer was used in the recommended dose of one tablespoon per plant (598.5 ppm Ca^{2+}, 456.75 ppm NO_3^-, 0 ppm NO_2^-), and two/four times the recommended dose. A control group with no added fertilizer was also monitored. Acephate by 97UP was used to monitor the effect of insecticides on guttation. The concentration of acephate in guttation was measured for two weeks after the initial dose of one gram per liter. Lead nitrate salt was added to measure the lead concentration in guttation. Lead was added into the solution at 0 ppm, 400 ppm, 800 ppm, and 1200 ppm. Standard 1 mol/L NaOH solutions are used to tune the hydroponic water pH level. The pH level started at 6.5 after initially leaving the plant in water for three days. Thus, we added NaOH solution to adjust the pH to 7, 7.5 and 8 to analyze the effect of the pH change on the plant roots and its impact on plant guttation.

Results indicate that nitrate and nitrite concentrations increase with higher dosages (Fig 6.a, b). Continuous low nitrate levels may suggest barren soil, requiring nitrogen fertilizer. Excess nitrate (above 5 ppm) or nitrite (above 0.5 ppm) indiciate too much nitrogen in the soil, necessitating reducing fertilizer or adding extra water. High nitrate (above 10 ppm [59]) or nitrite (above 1 ppm) levels warrant caution when consuming the plant, requiring testing or waiting for levels to normalize before harvesting. Additionally,

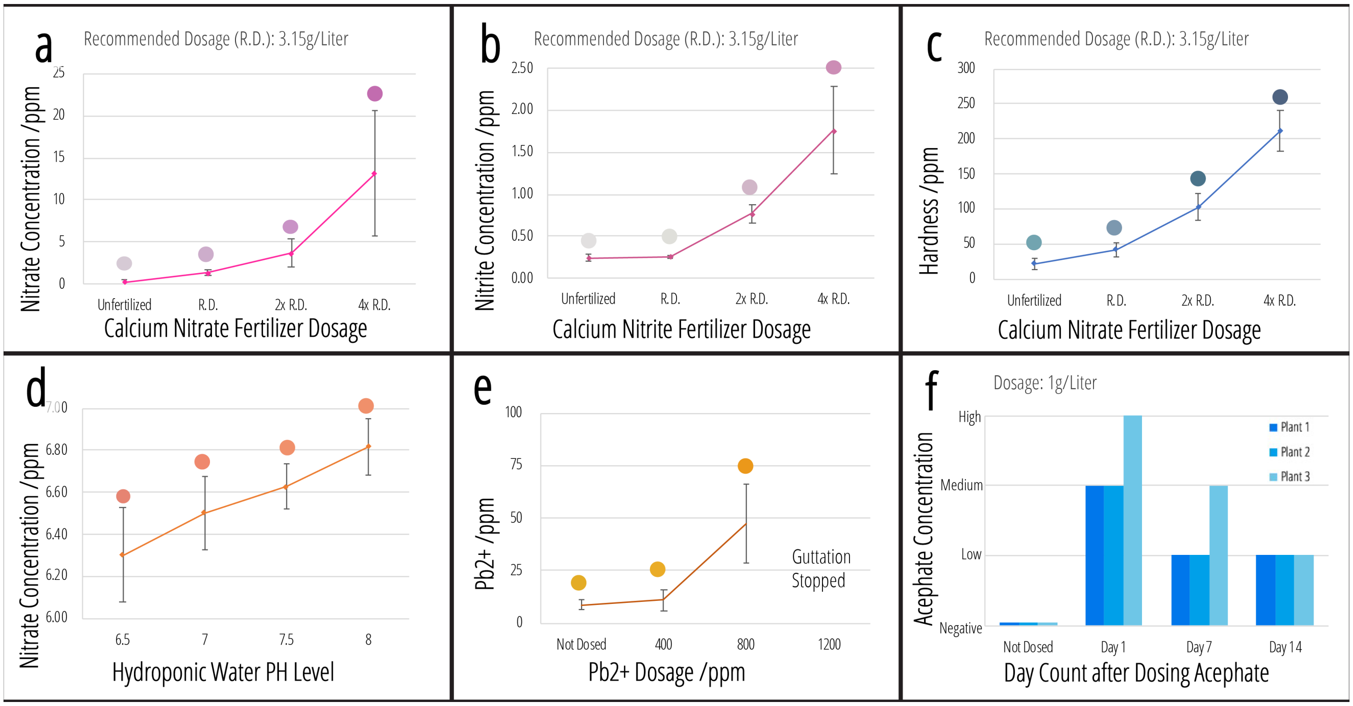

Figure 6: Quantitative guttation detection experiments using the sensor. Nitrate(a), nitrite(b), hardness(c), pH(d), lead(e), and acephate(f)

there's a positive correlation between water and guttation hardness (Fig 6.c). Hardness exceeding 100 ppm can be harmful to plants, allowing users to identify excess calcium and magnesium in the soil. There is also a positive correlation between the soil and guttation pH (Fig 6.d). If the pH level of the guttation is outside the optimal range (6-7), it could signal unfavorable soil pH for tomatoes [1]. Guttation in tomato plants contains relatively low lead levels compared to the the soil solution (Fig 6.e). This may be because tomatoes absorb minimal lead through their roots or retain some lead ions in their tissue instead of expelling them. We noted a slight increase in lead ion detection in guttation when root lead concentrations reached 400 ppm, with a significant rise at 800 ppm. EPA guidelines limit soil lead to 400 ppm for gardening. Even slight variations in guttation lead ions should alert growers to take action, such as collecting soil samples for further analysis. Guttation cessation happened at a 1200 ppm lead overdose. Acephate concentration levels show a gradual increase after exposure (Fig 6.f), persisting even after two weeks of initial exposure.

5 POTENTIAL APPLICATION DOMAINS

We propose several potential application directions of the sensor for HCI researchers (Fig. 7).

1) Improving one-to-one(s) human-plant(s) relationship. Our platform provides a novel solution for a better understanding of plant health and needs. We may leverage this to build educational courses and tools [37]. Moreover, although caring for plants has been shown to improve mental health, not everyone is good at taking care of plants. The stress associated with cultivating the plant may result in negative health and well-being outcomes [17]. We may build upon the technology to develop smart cultivation devices to facilitate cultivation (Fig. 7.a) increasing the likelihood of positive health outcomes. Lastly, we may develop novel and convenient research methods or tools for plant scientists.

2) Improving human-plant relationships on a large scale. If widely deployed, with all the data it collects and the network it builds, our platform has the potential to be adopted to perform environmental quality monitoring, assisting in urban and rural planning. (Fig. 7.b).

3) Bridging human-third species relationships. Human activities have greatly changed the environment. For example, small amounts of pesticide residue in plants that are harmless to humans may be fatal to pollinators [3]. We can potential integrate output modalities like shape/color-changing that other species may appreciate (Fig. 7.c).

4) Bridging human-human relationships. One may leverage our platform to prevent plant disease from spreading to a neighbor's garden, or neighbors can compare their plants' micro-environments and learn from each other's planting experience; the plant status can also be shared with (remote) relatives, friends, or experts, promoting a better co-management experience.

6 LIMITATION, FUTURE WORK AND CONCLUSION

While the guttation sensor is single-use, it is very low-cost and requires very little material to make, and can be easily disassembled and sorted before disposing. Seeking new material to replace

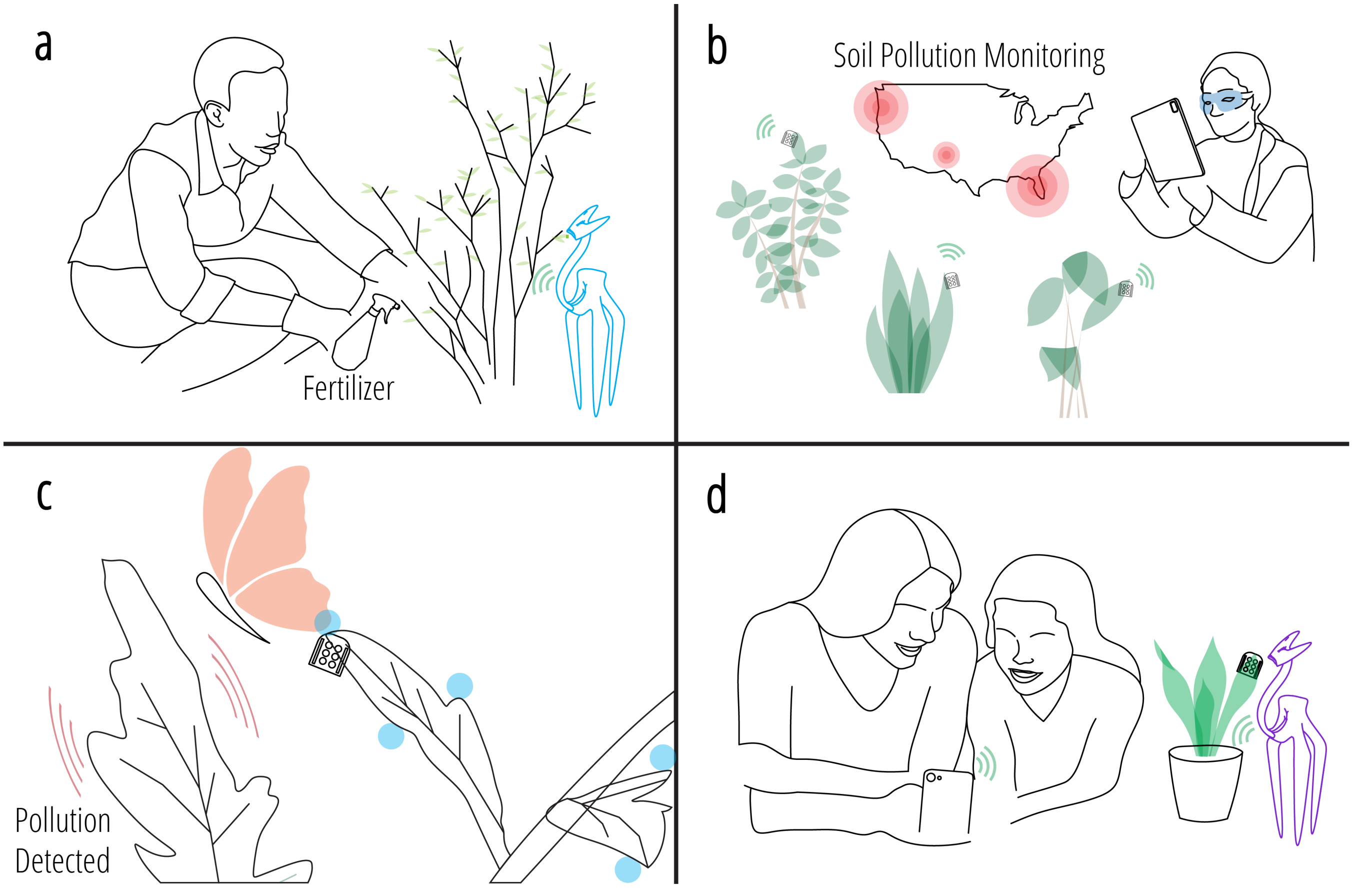

Figure 7: Potential application domains. (a) Improving one-to-one(s) human-plant(s) relationship. (b) Improving human-plant relationships on a large scale. (c) Bridging human-third species relationships. (d) Bridging human-human relationships.

the polymer enclosure and mounting can potentially make the entire sensor biodegradable. The sensor itself is capable of being a carrier for many kinds of off-the-shelf colorimetric test strips. But it is worth noting that while the majority of test strips can work in a wide range of conditions, certain strips may require specific conditions to react optimally. For example, the acephate test strip requires a temperature near or above 22°C to react quickly. Other limitations include the sensitivity of some test strips and the lack of colorimetric test strips for certain chemicals. However, there is ongoing research by chemists to develop new indicators for creating new and more sensitive test strips [15, 45, 54]. Furthermore, the current sensors possess a fixed form. Developing parametric design and simulation tool may empower users to customize sensors that align more closely with their specific requirements [26, 63]. Finally, the integration of supplementary devices such as cameras or color sensors can enhance the interpretation of the guttation sensor.

Our in vitro experiments demonstrate that our technology can functionally work, and we believe our Guttation Sensor can serve as a research and prototyping tool for researchers, amateur plant enthusiasts, and gardeners. To push the technology further, we are planning to continue iterating on and evaluating our technology by improving water resistance, accuracy, robustness, etc. From a user experience perspective, integrating more qualitative methods, such as interviews and focus groups, would offer valuable insights into how users interpret sensor data. This approach can significantly enhance the understanding of human-plant interactions.

In summary, this paper presented the Guttation Sensor, the first on-site and low-cost sensor for guttation detection. We introduced the development of the technology. Then we carried out evaluations, including in vitro experiments. Based on the results, we speculated and discussed how this platform could be adopted by various users, including researchers and designers, to develop technologies and design products that promote human-plant relationships in several directions.

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