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(INVITED)Sustainability, livability and wellbeing in a bionic internet-of-things

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A B S T R A C T

To address climate change, environmental monitoring and wellness more generally on a global scale, a new concept is presented - the bionic internet-of-things, or *b*-IoT. We propose the utilization of existing organic "sensor" technology that nature has provided and discuss a future adapting these to an existing inorganic internet to truly open up a global IoT. The use of organisms, in the first instance plants, bring an additional physical and psychological factor, connecting up living in things in a way that is consistent with natural symbiosis but extended over a global and potentially galactic scale. These plants not only monitor the environment, they interact to enable it to thrive, producing an ecosystem that consumes CO_2, generates oxygen, recycling land and providing an environment for other organic species to develop. In contemporary real estate development, the need for a more whole ecosystem approach is recognized and that technology plays a vital role towards that. Thus, we identify wellness and wellbeing as an integral part of all future technology development. A fundamental challenge is connecting such sensors to the IoT. We briefly review technologies of relevance in the context of material, health and environmental considerations, and discuss novel transducer mechanisms. To assess sensor capability, we review our recent work on measuring leaf material properties using contact angle mapping, demonstrating a diversity of potential for environmental monitoring from this method alone. We also review some examples of common botanical properties that already exist which can in principle be readily coupled to existing transducers to create the hybrid *b*-IoT. We briefly speculate into the future of materials at the sensor end and into reaching space that can meet low cost and provide advanced functionality to help connectivity and integrate fibre and fibreless technologies.

1. Introduction

It has been long hoped that low-cost sensors would emerge to transform the internet from a passive to an active smart internet-of-things (IoT) network system, or systems, over land, within water and in space. They continue to face numerous, often niche, challenges in material durability, maintenance requirements and power supply, features needed for self-sufficiency. This drives research across sectors from agriculture to industry and to infrastructure monitoring underwater, on land and in space [1–17]. Whilst many local demonstrations use predominantly electronic sensors, future global connectivity utilising a broader range of electronic and optical technologies is critical for addressing climate change and other international challenges. The role of materials towards this comprehensive goal is self-evident. High quality glass transporting near infrared light enables global connectivity that was not possible with fibreless technologies. These include geostationary satellites that use the radiofrequency spectrum generated from semiconductor materials to overcome atmospheric attenuation. Low earth orbital (LEO) satellites, potentially operating at shorter frequencies including in the infrared, hope to reduce but not eliminate the temporal delay with their counterparts in Clarke's orbit. However, they come at a price with tens of thousands needed to make up for their positional drift around the earth. These have relatively low-cost attractiveness for addressing connectivity in remote regions where population densities are low, such as on high technology farms streaming data from the land. But they pose a novel conundrum. There is a need for cross-border regulatory cohesion and goodwill to manage fibreless LEO satellites because they are the only moving sensor network that traverses multiple air spaces. Their deployment as a global communication network for sensing also raises other existential challenges given their own environmental impact in part arising from the materials that constitute them [8,18–22]. For example, the present technology in one year effectively introduces more aluminium (Al) into the upper atmosphere on re-entry, either through lifetime expiry or

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through rising space travel collision, than the entire amount introduced via meteorites. This accumulation of Al, often at the Earth's poles, may accelerate global warming [23,24]. From a materials perspective, this a timely reminder that the growth in exotic materials within electronic and optical devices will create other unexpected challenges throughout their derivation and incorporation phases.

Historically, easily accessed materials have been disruptive. Suffice to say at this point in time that without silica, both passive and with gain, the internet would not exist. It is with some irony that the development of optical fibres was originally driven by laser and amplifier work that became crucial for its application in telecommunications. Their ability to support and transmit tremendous volumes of data through low loss glass is unmatched by any other technology. And with novel material processing, it is supported by a range of extended fibre and integrated silicon technologies that will soon bring dense wavelength division multiplexing (DWDM) from the laboratory to the field [25–27]. Processing existing silica fibre technologies that can also support dopants and other materials such as aluminium oxide, has led to the demonstration of waveguides that can operate above 1200 °C [28], making optical technologies ideal for extreme conditions including off world. With few exceptions, more varied fibreless technologies are presently confined to the fibre ends or edges of the internet where mobile transport has become a necessity. Increasingly, the existing fibre network is becoming smarter, no longer confined to transmission but actively acting as intelligent sensors. Consequently, hybrid fibre and fibreless global networks going beyond current data transfer over optical fibres are integral to full human connectivity more generally, notwithstanding both the potential and risks of global and local governance. A tremendous centrepiece challenge has become the ability to couple any sensors signals directly into optical fibres, where very few solutions presently exist.

The recent SARS-Cov-2 pandemic has widely reinforced the need for faster evolution of the IoT. Globally tracking pandemics in real-time [11] can transform health to quickly suppress outbreaks, a situation that is doable with today's technology. Secondary detection technologies, whether in bioanalysis or in diagnostics, and vaccine developments have benefited from this pandemic. Materials also play a role in direct prevention of spread, whether as antiviral surfaces or with semiconductors emitting in the UV down to $\lambda = 240$ nm to denature the virus whilst potentially mitigating cancer risk [29,30]. Something as simple as not enforcing infrastructure and aviation compliance in modifying and treating aircraft with appropriate technologies undermines medical precautions to prevent transmission. SARS-Cov-2 and its variants are now globally ubiquitous and adapting at a rate that is outpacing even the rapid developments of newer therapeutics. A tremendous and unexpected consequential realisation was the psychological factors that impede action and development and subsequently the wider degradation of public health mentally and physically, bringing renewed attention to research in this space. Until now, technology has distanced itself from such considerations. Here, by way of example, we point out that a bionic IoT can address some of the psycho-social aspects by considering the aesthetics of the sensor.

Ideally, as the full potential grows our understanding of the IoT needs revaluation from the way consumers engage to how society functions whether as smart villages, cities, countries, planets, or smart galactic outposts on the moon and beyond. The management of such systems involves long term developments in materials, devices, sensors, and signal processing, both passive and active, potentially opening genuine artificial intelligence in time. Indeed, it is often forgotten that all life and consciousness, including human, is predicated on a critical mass of interactive sensing capability with the environment. At the core of all this data and signal generation and processing are the sensors themselves. However, traditional sensors in the IoT are not always robust, autonomous nor reliable long term, and their fabrication involves substantial deleterious climate impact that has largely been ignored. An exception has been the significant effort to develop self-powered devices that can operate indefinitely, using a variety of interesting means [31,32]. New optical materials such as perovskites for solar activity under low lighting conditions [33] are playing a key role. Despite these efforts, the sensor itself remains unchanged in concept - a low-cost, traditionally manufactured simple structure, preferably a mass-producible silicon or silica-based device, often targeting an individual parameter. More expensive in implementation to date has been optical fibre sensors [34], although new developments in 3D printing may provide novel and lower cost fabrication variations [35–39].

In this article, a different approach to sensing is offered. One that foresees a future of climate friendly environmental monitoring using instead existing, and later modified, "natural" sensors that can, in principle, be integrated into the network [40]. These bring additional benefits, including health and wellbeing for the wider community and environment. Integrating organic species directly into the IoT represents a disruptive approach to sensing and to the way we perceive the world. Humans are already integrated into that IoT, either subservient or controlling it (reminiscent of the fictional Eloi and Murlocks in H. G. Wells *The Time Machine* written in 1895), so it makes sense other species could be directly utilised as well. The *b*-IoT itself is a hybrid organic-inorganic ecosystem bringing together largely inorganic material and sensor technology, today mostly based around, but not limited to, silicon prepared by chemical vapor deposition variants, with natural organic materials often in self-assembled form, and sensor systems. Importantly, the motivation behind these developments rests on a larger need: to improve the livability and wellbeing of society and its inhabitants through the integration of sustainable and environmentally friendly internet technologies [41], identifying the core scalability and impact challenges of current IoT approaches.

2. The bionic IoT

The *b*-IoT integrates organisms directly into the network, in the first instance as sensors that can be used to monitor the environment. Although not the subject of this paper, humans have informally been exploiting organisms to undertake predictions for millennia and are already integrated into the internet with many businesses subtly manipulating, and managing if not directing, human affairs, raising significant existential and ethical challenges for society. Farmers already monitor their livestock, using them as sensors - cattle, for example, are said to lie down when a storm is approaching corresponding to a change in temperature they pick up through their abdomen. Animals have an array of powerful sensing capabilities that go beyond human sensors. Birds are known to fly in large clusters with an approaching storm, detecting both barometric pressure changes [42] and potential static charge changes in the atmosphere. On the other hand, more astute observations have noted that the presence of a swarm of ladybugs predicts warmer weather [43]. These correlations are characteristic of the sensing features of animals and insects that go beyond those of a human, reflecting unique organic material systems - they can be used in much the same way as artificial sensors are similarly designed to be used and therefore can be integrated into the wider IoT. An interesting mammalian example is the platypus which uses a combination of mechanical pressure and motion detection along with electroreception, picking up electromagnetic emissions similar to plants and insects [44,45] in the water to detect prey demonstrating data fusion combining multiple sensor signals in nature. More generally, many organisms avoid anthropomorphic sources of electromagnetic waves such as from power lines, a reason concerns on human impact remain amongst environmental activists. Importantly, there is currently no research undertaken on the ecological impact of so-called wireless (or fibreless) generation, an issue that is likely to grow as emission sources spread farther into the field and as well shift to higher energies. For reference, it is known that the platypus experiences significant stress and early mortality because of interference from signals within an artificial tank design for public display [46]. Such research more widely could in principle be done within the *b*-IoT just simply by monitoring the organic sensor performance over time. This provides environmental monitoring more generally including the impact of transmission technologies.

2.1. The bionic IoT and human health

Such studies become important for human health because the fact that humans are not thought to be receptive to these does not exclude potentially unidentified or unresolved impacts. Radiofrequency (RF) radiation (30 kHz-300 GHz) is recognized by the International Agency for Research on Cancer (IARC) as a possible human carcinogen [47,48]. More recent studies on the impact on human [49] and mice studies [50] strengthen concerns and RF exposure is ranked by some as a Group 1 carcinogen, a classification on par with nicotine exposure. Therefore, the rapid deployment of 5G at shorter wavelengths, higher energies and stronger absorption has led to a consortium of scientists writing to the European Union calling for a moratorium on its deployment until more research is undertaken [51]. Because of the scale and potential for IoT to disrupt society and indeed civilization as we know it and therefore underpinning wealth and power, that call has been ignored. This is accompanied by a standards sector that is not moving away from a conservative and restricted focus on ionizing radiation for wireless communications based on thermal effects alone, ignoring oncological and engineering [52] including the effects on animals. It raises disquiet by assuming harm can only occur with ionization alone. It is with some irony that, more broadly natural organic sensors use approaches that would be expected to be impacted by background wireless, such as electroreception. Many researchers, for example, are attempting to mimic electroreception in future undersea detection by submarines, drones, and divers. Ultimately, the identification and acceptance of health impact and its mitigation might instead come from the presence of a bionic IoT.

2.2. Hybrid fibre & fibreless technologies and connectivity

Both natural and artificial should, in theory, be possible to further combine and hybridise through integration with the internet and there is growing precedence in this space. In agriculture, plants are used to monitor and optimize their growth and immediate environment, the basis of agricultural technology, or AgTech. Much technology has been developed and is available commercially around specific sensors to measure plant parameters primarily to optimize their health and to develop precision agriculture [53,54]. This includes a shift of farming into smart cities using maturing aquaponics technologies and cellular agriculture [55,56], threatening to disrupt traditional, regional farming. In this work, we propose combining the internet with plant sensors not for monitoring plant health or for AgTech per se but for using plants as specific sensors for the environment and industrial applications, beyond their own needs. Some reference has been made in the area of cyborg plants [57–59], where plants are used to support additional sensing parameters through implantation of materials such as, for example, carbon nanotubes to directly and discreetly detect motion in a field, an interest in defence. These too can be integrated into the wider *b*-IoT, which is taking the existing and future communications and data transmission technologies of the internet to make use of the data from plants to better understand the environment and to do so on a global scale. Such a system can be used to quantify and monitor precision climate change.

A depiction of the current IoT is shown in Fig. 1. Global connectivity is key and that requires access by all. The global bionic IoT utilises mainstream and future transmission internet technologies coupled with organic sensors both on world and off world. In the figure, the moon is shown together with both low earth orbital and geostationary satellites. The moon is a potential early interplanetary mining centre for extending material access on earth, including rare earths [60]. Extending communications and data transfer from the earth and into space and back

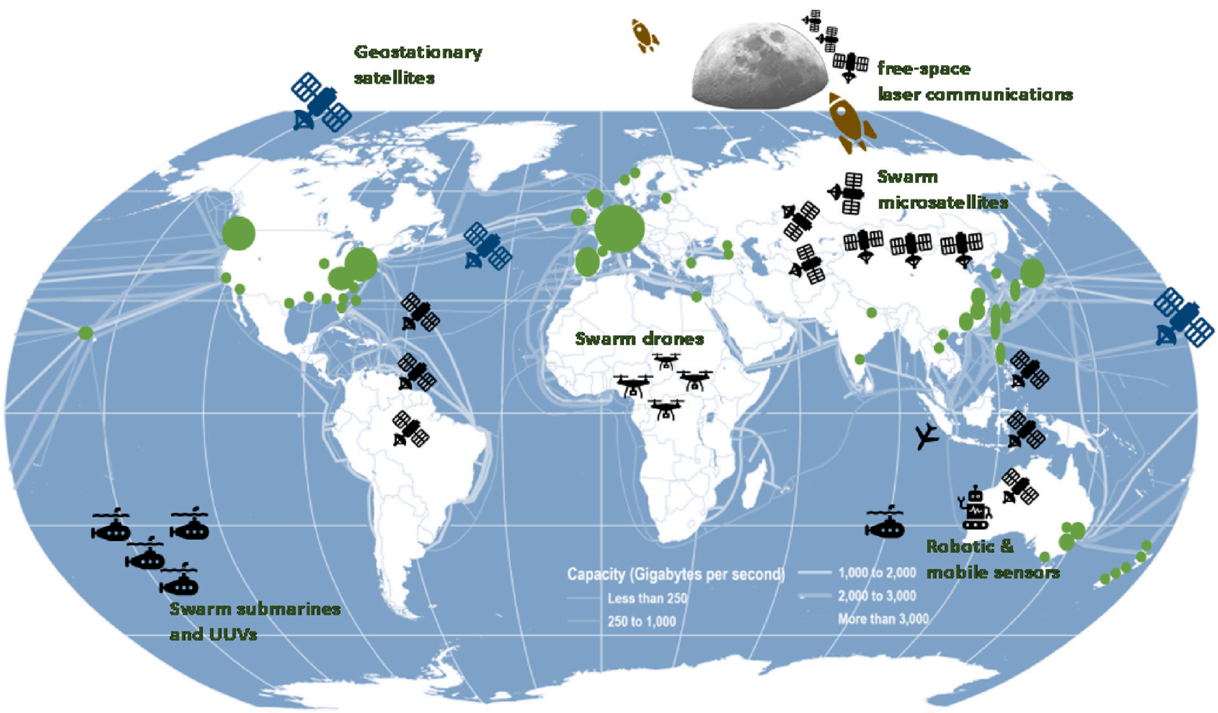

Fig. 1. The global bionic IoT uses mainstream and future transmission technologies coupled with organic sensors both on world and off world, in this case the moon is shown together with both low earth and geostationary orbital satellites. At lower altitudes, drones both in the air and underwater provide mobile sensing technologies to gather data. One example is the Aucuba Japonica plant which is distributed globally as shown in green. This plant is conveniently located to many optical fibre hubs where attached transmission devices can couple data information directly using novel optical transducers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

again will be enabled initially by satellite including low moon orbital and geostationary satellites over the moon, rocket and self-sufficient solar sail and power routers using free space communications. This may later potentially be extended by near infrared supporting optical fibre cables fixed to geostationary centres over the moon, and earth and in-between swarm satellites, to increase bandwidth and security [61]. To reduce weight, ultrathin fibres well below the standard 125 μm can be used - a reduction by half leads to a mass reduction of four. Using thin fibres down to 25 μm [62] scales this reduction by more than 17 suggesting the technology for these space cables exists. Additional strength needed to support the silica mass can potentially be provided by carbon nanotube composite coatings [61,63]. Unlike undersea cables, these cables can access solar optical power directly, generating electrical power for the diode-pumps that excite the various rare-earth doped fibre amplifiers ensuring signal is not lost, a system that is potentially much easier to install and maintain. This also has advantages over free space laser beam propagation, the ultimate in directed beam transmission, which experiences substantive atmospheric absorption. These cables could also be attached to proposed space elevators [64,65].

Optical fibres, through extraordinary silica and silica-amplifier assisted transmission over 30 000 km, overcomes the tyranny of distance, corners, and speed to connect the world today and tomorrow potentially beyond. Through quantised confinement of light in tight transverse modes in space and in momentum, it outperforms free space communications in any wavelength and will also play a key role in space where infrastructure is permanent. In practice, as Fig. 1 shows, not every site on the planet can be physically linked and generally cable laying costs determine mostly high-density populations receive optical fibre cables.

Fibreless, or wireless, data transmission, using any part of the spectrum, is largely an end technology of importance today for mobility and as well regional access to the internet. In Australia so called "salt & pepper" connectivity is a significant problem in the implementation of precision agriculture [8,66]. It can be collected or transmitted using singular or swarm numbers of connected satellites in geostationary orbit or in currently popular low earth orbits (LEO), with the various environmental challenges this entails. Undersea communications between underwater vehicles, both submarine and drones, and individual scuba divers is another contemporary area in telecommunications. Optical fibre coupled with novel liquid crystal mirror-based optical transducers plays a key role in technological convergence [67], bridging the fibreless domain with land and sea. Undersea, long wavelength acoustic technology is popular and for higher frequency communications over shorter distances, determined by sea water attenuation, blue laser diodes are used. Vibrations on the sea surface arising from communications can be picked up by RF to establish a hybrid acoustic-RF link with an overflying aircraft, demonstrating a way to converge technologies to suit the transmission medium [68]. Interestingly in space, so far as mobility is concerned, optical direct free space communications is likely to become the single most important technology, with shorter wavelengths as low as UV allowing very high bandwidth capacity [69]. This bandwidth could in principle exceed that of near infrared optical fibres when free space beam angular momentum and beam shaping can be controlled. The absence of an atmosphere makes this feasible since there is no UV absorption band edge characteristic of materials. Further, the problem of noise from background light from the sun is negated because the blackbody radiation falls to near zero the deeper into the UV.

Silica optical fibres are so remarkable however, that they go beyond transmission - since they do involve a material system, they are not completely passive and are impacted by the thermal background of the material and its own sensitivity to the environment. This means existing optical fibres lain down for telecommunications, both used and dark, can now be used to monitor earthquakes and other seismic phenomena including missile strikes anywhere on earth [70]. The wide operating range of optical fibres allows them to be deployed in more remote and extreme locations, such as in the Arctic [71], a precursor experiment to assess sensing technology in space at locations known to have seismic activity including the moon [72] and Mars [73] two target destinations for human occupation. Those thermal motions in the optical fibre are impacted by external heating or vibration. By using a combination of time-of-flight pulse modulated transmission along with machine learning, characteristic vibrations, or sounds, can be identified. This is an ideal detection, security, preventative and maintenance tool within cities that have cable deployed everywhere and spinoffs now exploit existing used fibre and backup capacity in unused, or dark, fibre for various applications. This phenomena can go further and be exploited to create super-sized optical transducers, nominally known as distributed acoustic transducers (DATs) [74] - that is a tool for converting incoming sensor signals from other sensors and devices in one domain directly into the optical domain, greatly extending their transmission capability potentially offering superior performance over existing technology based around liquid crystals. A schematic of how it would function within a smart city is shown in Fig. 2. Such technology when combined with specialty coatings that convert other signals, such as heat and light, to strain would be ideal for integrating all sensors both inorganic and organic - that coupling can occur anywhere along a fibre with precise identification of location and time rather than at the ends is disruptive and will make true IoT and *b*-IoT possible.

3. Plant sensor case study: Aucuba Japonica (Japanese Laurel)

To assess the potential for the *b*-IoT, we have focused more immediately on plants. The principles can apply to all other organisms and life forms. A common and hardy plant species originating across Asia, Aucuba Japonica (or Japanese Laurel), has become naturalised in many locations across the globe. Aucuba Japonica is a compact evergreen plant often, but not always, with green-yellow variegated leaves used in natural medicine [75], including in the potential treatment of poisoning [76]. However, it can also be a poison, problematic for pets when used as an indoor plant [77]. The variegation is particularly interesting because it arises from decreased chlorophyll and increased carotenoids, with no structural differences between green and yellow regions [78]. Accordingly, there is decreased photosynthesis. There is some confusion in the literature with Wikipedia claiming the yellow is due to Aucuba Badnicus [79], a virus infection that creates yellow features in Laurel leaves [80]. However, the variegated healthy form is genetic in origin. It was introduced in the southern UK from Japan in 1783 and became widespread across woodlands by 1981 [81]. The high global prevalence of this plant, including in Australian and New Zealand subtropical zones in the southern hemisphere (Fig. 1), demonstrates its remarkable hardiness. This makes it a potential candidate for a distributed sensing network that can help monitor the environment and the global impact of climate change. More conveniently this naturalization has followed developed, populated areas close to optical fibre transit hubs making it a candidate for future *b*-IoT sensors if useful measurands can be extracted. This overlay with the optical fibre network is shown in Fig. 1 and is the reason we have selected this species to assess as a sensing element.

Fig. 3 shows both a typical variegated Aucuba Japonica and as well the plant clusters growing along a busy road in Shanghai, China. These plants are used to brighten areas including roadways to make the views more pleasant for travellers and nearby residents. This aesthetic factor, central to mindfulness and well-being, is a key reason the *b*-IoT is especially important in addressing climate change and environmental monitoring. We review our recent work in assessing these plants. Plants make ideal practical, low-cost sensor alternatives to contemporary physical hardware traditionally used to monitor a range of environmental parameters such as air quality and health. Of interest is the robustness of this plant over time. The Aucuba Japonica has a relatively thick top cuticle layer over the dermal tissue system, or epidermis, which is a layer of cells without chloroplasts coated in cutting and waxes. The heterogeneous cuticle layer (Fig. 4) contains the insoluble polymer cutin, solvent-soluble cuticular waxes, polysaccharides and

Fig. 2. A simple underground optical fibre where light traveling down the fibre acts as a novel transducer picking up signals from multiple sensing technologies and formats. Physical and acoustic signal outputs from sensors are directed towards the fibre in a targeted fashion to introduce strain at various points. Specialty coatings, some of which already exist having been demonstrated in other kinds of optical fibre sensors, on the fibre can also receive and convert optical and RF absorption into strain detected by the interrogating light within the fibre. Time of flight along with trained machine learning algorithms identifies which sensor, what the signal means and when in real or near-real time.

Fig. 3. The Japanese Laurel (Aucuba Japonica) is characterised by green leaves that can have varying degrees of yellow (a), consistent with decreases in chlorophyll, and bright red fruit (b). It is a common aesthetic plant prized for its robustness, independence, and ability to brighten up shaded areas. The plant is dioecious and so only half can reproduce. The plants assessed in the reported work are shown in (c) where they are sheltering under a tree away from a busy street in Shanghai, China and in (d) where they are located on a strip beside a street with heavy traffic. This allows a comparison when they are exposed to varying conditions including car particulate matter, sun, wind and rain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

often cutin. Cutin is an aliphatic polyester built from C16 and C18 ω-hydroxyfatty acids and their derivatives. Primary components of the cutin C16 monomer family are 16-hydroxy palmitic acid and 9,16- or 10,16-dihydroxypalmitic acid [82]. The cuticular waxes are embedded within the cutin matrix, an intracuticular waxy layer, and additionally deposited in the outermost layer, as either wax crystals and/or wax films, forming an epicuticular waxy layer exposed to air [83]. This impressive natural material composite system ensures the leaf is hydrophobic, minimising transpiration and preventing unwanted water ingress. What water, carbon dioxide and oxygen is taken in or expired is through controlled fashion via the stomata. Additionally, cuticular membranes attenuate ultraviolet radiation through reflection [84] whilst allowing transmission of optically relevant wavelengths for photosynthesis further inside the leaf [85]. Another important aspect from a sensing paradigm is mechanical robustness. These membranes are viscoelastic which helps to reduce the risk of mechanical failure in wind and heavy rain and accommodates expansion during growth or shrinkage during aging, degradation, or illness [86]. Importantly, these cuticle layers are not passive structures and change dynamically with useful elasticity to assist both the plant and their own preservation - upon hydration a lowered stiffness and an increased extensibility is reported for enzymatically isolated cuticles [87]. Such mechanical changes can in principle be measured directly by appropriate strain sensors and changes transmitted to the backbone optical fibre for cloud processing and monitoring.

Given the properties of the cuticle layers (Fig. 4), degradation over time is expected and this is seen in normal lifetime of plants, especially when exposed to sunlight. In the case of Aucuba Japonica, it prefers shade for these reasons, noting that the variegated yellow regions indicate reduced shorter wavelength reflection overall. That response to sunlight, in turn, makes them the ideal choice for sensor evaluation providing a potential frame of reference. Given the role of the cuticle layers in potential sensing applications, and to couple these with IoT related instruments, we characterised the surface properties by measuring surface contact angle of water drops using a customised smartphone analyser. This builds on a wider trend towards the use of smartphones for sensing and environmental applications because of their versatility and modus of operation at the IoT edge [88]. It is possible because we have previously shown that top-down contact angle measurements performed on orchid plants can be as accurate, if not more, than standard side measurements [89].

Top-down measurements not only relax the stringent requirements for an instrument but allow rapid measurements by permitting for the first time full contact angle mapping (CAM) of a surface [90]. Single

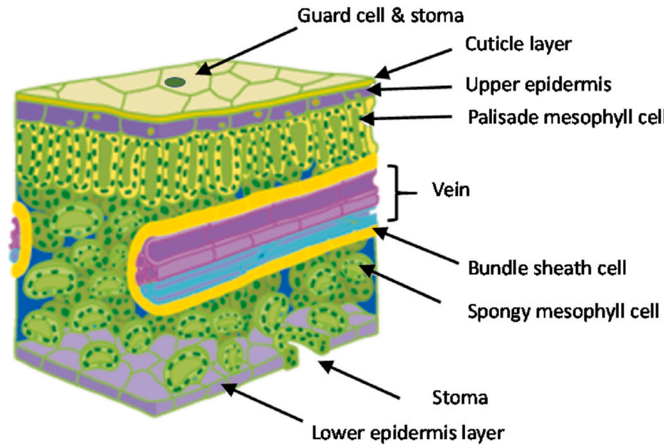

Fig. 4. A schematic cross section of a plant leaf. The plant structure is complex but contained within the cuticle layer, made from a range of cuticular waxes held together by cutting. These are hydrophobic materials. The cuticle is known to change over time and interact dynamically with the plant - it is impacted by external environmental factors, making monitoring of the cuticle potentially useful for sensing the environment. In some plants multi-periodic structures can appear in the cuticle or when chloroplasts line up, or both, in such a way to give rise to structural colour in addition to any pigmentation-based colour. These properties have physical counterparts in bacteria, insects and other organisms. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

image analysis of multiple drops replaces sequential analysis over meticulous sample cutting, extraction and preparation over a surface. This reduces the errors between measurements and allows data accumulation for more accurate averaging of the contact angle and its variation and error over a surface. In this work the image is taken with a smartphone. Overall, the contact angle is sensitive to change in surface properties, both mechanical and chemical, thereby providing insight into broader changes. Other properties can be explored directly, including strain measurements. These are changes imposed by changes in the environment. Consequently, the hybrid integration of living and non-living technologies in this way opens up the scope of the IoT more broadly, the basis of the *b*-IoT.

The underlying principles demonstrated here have significant ramifications for policy more broadly in other sectors, including industrial and agriculture – simply having healthy plants on site can relax monitoring demands for all site workers, for example. On agricultural land, plants offer other enormous benefits in recycling soil virility over time and improving local climate but as well of detecting earlier of deleterious changes in the climate and environment that allows earlier preparations to be initiated. In botanic gardens, plants play a major aesthetic and environmental role for city health - proactively using these to monitor the environment benefits the city. Making all these regional and city hubs connected via the internet opens up endless possibilities tracking real time changes on a global scale, much the same way that has been proposed for medical tracing of pandemics [11]. The possibility exists of using crops and botanic gardens, private gardens and deliberately distributed greening of towns and cities as well as industrial sites in a similar fashion for distributed and networked sensing. Apart from providing an alternative to conventional inorganic IoT technologies, the *b*-IoT offers aesthetic and health benefits, from natural air filtration to temperature stabilisation in cities through to wellness improvement more generally. It also can help bring back native wildlife including smaller birds that have been pushed out of the cities. This alone will transform industry and community because plants can self-monitor the *b*-IoT as well as their local environment, ensuring safety for humans.

3.1. Contact angle measurements

Measuring the wettability using drops of water on organisms can be challenging. For leaves this is because there is surface irregularity arising from varying curvatures, roughness, absorption, and reflection from its unique cuticle structure, features that make side measurements of contact angle unreliable. At first consideration, these variations might make such measurements unreliable, prone to large error variations. For this reason, the original work was conducted by collecting samples from the field (shown in Fig. 3 (c) & (d)) into a controlled environment where the contribution of these variations can be monitored. A schematic of the contact angle analyser is shown in Fig. 5.

To access the leaf away from the edges involves cutting samples into pieces. Top-down contact angle (CA) imaging (where the drop is imaged from the top and the CA extracted from diameter measurements) can circumvent these problems and map CA distribution over the actual leaf, providing more information and data about a leaf's overall wettability. A laboratory demonstration was previously used to characterise orchid health [89,90]. To enable this in the field, a smartphone is used as the image capturing and measurement tool for on-the-spot diagnostics, taking CA measurements out of the laboratory. Importantly, using a connected device such as a smartphone opens opportunities to later couple multiple devices in various locations – so-called swarm technologies such as those proposed for addressing pandemics [11]. Cloud analytics can simultaneously collect, integrate, and analyse the data to provide additional information and insight that can be sent back to multiple users. The advantage of networked sensors is large data generation that can help circumvent challenges involved with less accurate individual measurements – these networked super instruments generate resilience to individual instrument error. This will form the basis of novel, hybrid organic-inorganic bionic IoT.

The practical deployment of this analyser involves sample preparation and the deposition of precise volumes onto the samples. The need for this volume precision is because top-down CA measurements derive the CA from a spherical caplet approximate of a drop on a surface. The measurement of the diameter of the drop combined with its precise volume allows extraction of the CA for two conditions: hydrophilic and hydrophobic. Hydrophilic surfaces have a CA lower than CA = 90° and hydrophobic surfaces have a CA higher than CA = 90°. Super-hydrophobic surfaces are characterised with CA > 150° [91]. If the measured drop caplet base radius is $r_{cap} = d/2$ m where is d is the

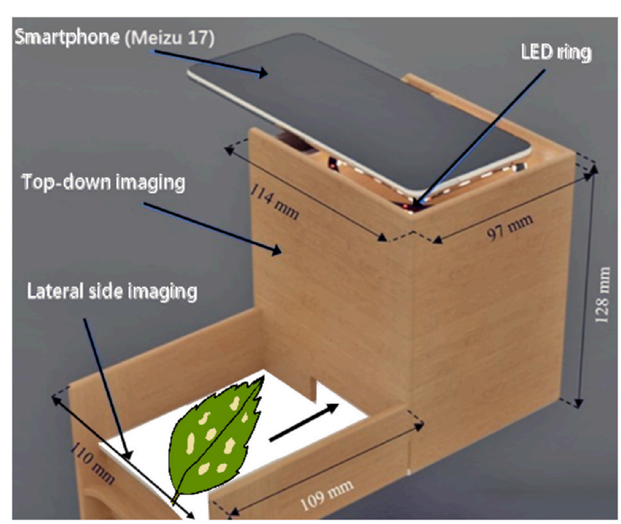

Fig. 5. CA smartphone-based analyser layout designed for portable use. Both top-down and conventional side CA measurements are performed on a leaf sample placed into the sample holding area. Top-down has the advantage of being able to map CA over an entire leaf surface whereas standard side measurements are confined to the edges.

measured diameter, the volume of the spherical caplet is given by:

$$V_{cap} = \frac{\pi h}{6} \times \left(3r_{cap}^2 + h^2\right) \tag{1}$$

From a known volume and using r_{cap} the height h can be calculated. If it is hydrophilic h will be less than r_{cap}. However, if it is larger, then the volume is not correct and instead, the following volume is used to obtained h [89,90]:

$$V_{cap} = \pi r h^2 - \frac{\pi h^3}{3} \tag{2}$$

The CA is given in both cases by:

$$CA = 2\tan^{-1}\left(\frac{h}{r_{cap}}\right) \tag{3}$$

Visual observation can show which regime one is in because the hydrophobic case has a band structure edge rather than a sharp edge, characteristic of two observable diameters, whereas the hydrophilic case only has the caplet base diameter. The process is amenable to flow diagram analysis for mobile phone app design.

In practice, a pipette (V = 0.5–10 μL; accuracy ± 5%) is used to create the droplets that have a volume $V = (4 \pm 0.2)$ μL. Water drops at this small volume ensure that surface tension is greater than the gravitational force so that a good spherical-shaped caplet is obtained. From the diameter of this caplet, obtained by top-down imaging, the contact angle can be derived in both hydrophilic and hydrophobic regimes (or omniphilic and omniphobic for liquids other than water). Given the non-standard top-down approach, the instrument allows simultaneous measurement of top-down and side CAs for direct comparison. The side CA measurements are extracted directly by fitting a tangent to the image from the side. To validate the measurement, a piece of tempered glass, similar to Corning Gorilla glass [92] was tested. It is an alkali aluminosilicate sheet glass with a highly compressive thin layer at the surface formed by ion exchange. The glass is said to be hydrophobic because of the fabrication process, which makes it easier to clean. On the tempered glass, hydrophobic caplets with diameter d = (3.1 ± 0.3) mm were obtained. After six measurements each, the respective CA measurements for top down and side were: $CA_{top} = (111 \pm 5)^\circ$ and $CA_{side} = (112.5 \pm 2.2)^\circ$, agreeing within error, the top down having a slightly larger error.

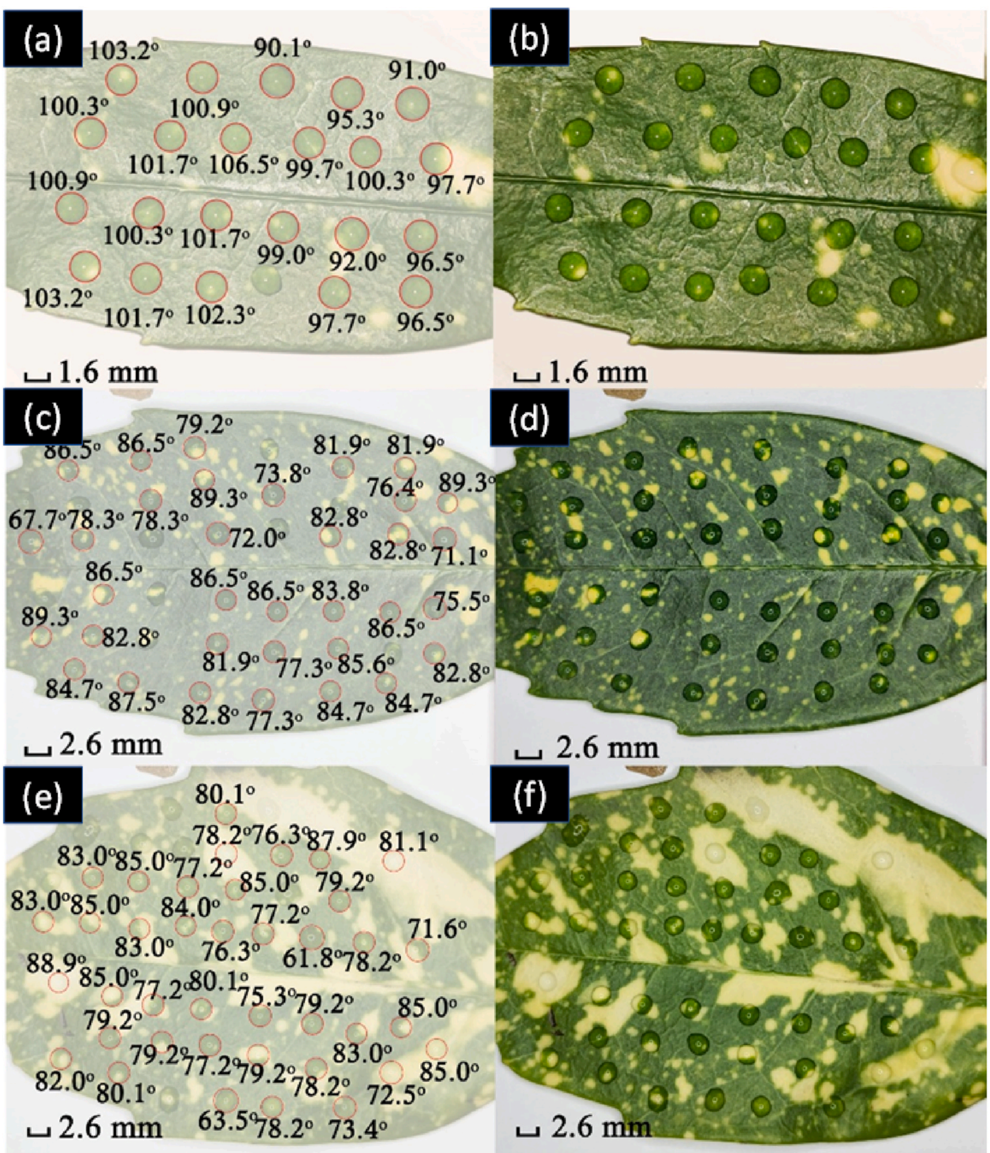

Fig. 6. Contact angle maps (CAM) and images of (a) & (b) a young leaf in shade, (c) & (d) a mature leaf in shade, and (e) & (f) a leaf exposed to direct sunlight. Images on the left show the measured data overlain on the image of the leaf with drops shown on the right for clarity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Review of results

3.2.1. Surface mapping of young and old leaves

Depending on location and planting times, the age of the plants varies and this does impact the quality of the cuticle layer and consequently needs to be considered. Within the same plants, young leaves grow at the top of Aucuba Japonica, displacing older leaves – therefore, these youngest leaves tend to be highest whilst oldest leaves tend to be lowest. Fig. 6 summarises the measurements obtained. By mapping over the entire surface, an estimate of CA variation due to surface variations can be obtained. In general, young leaves are observed to be more hydrophobic than mature ones although this can be affected by external factors such as solar radiation (shown in Fig. 6 (e) & (f)) and chemical impact such as soil pH. The differences between young and old also reflect degradation over time from duration of environmental exposure, including solar, chemical, temperature, rain and wind [93,94]. The immediate benefit of CA surface mapping (CAM) become clear when error ranges can be meaningfully determined. The mean CA for the young leaf is CA = $(99 \pm 4)^\circ$ and for the mature leaf CA = $(82 \pm 6)^\circ$, a notable difference of $\Delta\theta \sim 17^\circ$. There is an observable change in surface wettability from hydrophobic for a young leaf, to hydrophilic for a mature leaf. Side measurements limited to sample edges alone simply cannot provide a meaningful distribution and error estimate, making comparisons between leaves and plants difficult (see Fig. 7).

It was observed that for leaves directly exposed to sunlight compared to those sitting more in shadow without direct solar exposure (Fig. 6 e, f)) have a mean CA = $(79 \pm 6)^\circ$, which is lower than that of the mature plant within the shaded environment. The higher UV fluence the plant is exposed to is consistent with degradation of the cuticle epicuticle layer which, depending on intensity, may also be ruined, burnt, or partially destroyed. As for human organisms, there is accelerated aging of the outer layers with continued exposure, something that can be explored more thoroughly using exposure to an artificial UV light source. Correlating such a property would provide a novel approach to reliable solar monitoring in the environment over time.

3.2.2. Accelerated aging: exposure to near UVA light (λ = 365 nm)

Aucuba Japonica leaves were exposed to near UV (UVA) light (λ = 365 nm diode, P = 6 W, $I = (7.1 \pm 0.4) \times 10^6$ mW/cm^2, distance from leaf d = 9 mm). The setup and typical conditions used in this work are shown in Fig. 8. From the CA maps, the top of the leaf prior to exposure to UVA has a CA = $(91.6 \pm 2.8)^\circ$. After an exposure time t = 20 min (after 10 min, the orientation of leaf would change 180°) the leaf experiences a total irradiance $I \sim 1.4$ J). The mean CA = $(90.4 \pm 3.0)^\circ$, a slight decrease was observed but within error unchanged. Continued exposure with an additional t = 30 min, raised the fluence irradiance to $I \sim 2.2$ J. The mean CA decreased further CA = $(86.8 \pm 2.5)^\circ$, making the leaf on average hydrophilic. After a much longer continued exposure of t = 10 h (during the night), the exposure site turned black. This gradual aging process suggests the cuticle layer is slowly ablated by UVA light until at some point the leaf dermal layer underneath is exposed. UV light can directly strike the leaf underneath, which then burns. In Aucuba Japonica, the cuticle layer is estimated to be $d \sim$ (2–3) μm thick, slightly thinner than the cell layer [95]. It is the epidermal layer that is thickest with $d \sim 40$ μm. From this reference, the lower cuticle layer at $d \sim 1$ μm is indeed less than the top layer, explaining the observed differences in exposure times. When measurements were repeated for the layer beneath, there was a corresponding reduction of CA at a faster rate than the top layer, consistent with removal of a thinner cuticle surface layer.

3.2.3. Detecting pollution through surface wettability changes

The above measurements demonstrate the power of CAM to determine changes in surface wetting properties of a leaf surface. Once sufficient data can be extracted, the reliability and reproducibility is consistent even if lone measurements appear not to be. This suggests CA measurements and related surface wetting tools can offer powerful new alternative to environmental monitoring. To test the potential of this natural sensor for environmental monitoring the impact of pollution on surface wettability is examined. Pollution can drastically affect an environment, and so it would be expected to have an impact on both plant and human health. Consequently, the plant can also act as a monitoring instrument for assessing such pollution. For example, in densely populated cities, particulate matter from cars is an established health problem [96,97]. The concentration of particulate matter will be highest near heavily used traffic. Whether this matter was detectable through CA changes on the leaves of plants growing at and near a street is examined. Fig. 3 (d) shows the location chosen.

Compared to previous measurements of leaves away from heavy traffic in Shanghai, three tested leaves next to the road shown in Fig. 3 (d) are found to be much more hydrophilic. Mean numbers are CA = $(58 \pm 11)^\circ$, CA = $(52.6 \pm 2.5)^\circ$ and CA = $(46.7 \pm 4.0)^\circ$. This represents a significant reduction in CA of $\Delta CA = \Delta\theta \sim (30–40)^\circ$, consistent with a layer of particulate matter that absorbs and spreads water on the leaf and tries to keep it away [98,99]. This matter stems from the exhaust of vehicles from passing traffic and can visually affect the gloss of the plant. Among these leaves, there were poor drop shapes because of ridges on the leaf and other factors where particulates may aggregate in larger quantities. In this case, these drops were not measured as they no longer approximated a spherical caplet and will not be accurately described by equations (1)–(3). Moving away from the street, the surface properties were observed to change with increasing CA $\sim (88.5 \pm 4.7)^\circ$, $(92.6 \pm 2.2)^\circ$and $(96.0 \pm 2.2)^\circ$, going back to hydrophobic (Fig. 8 (d), (e), (f)). Similar results are obtained by lightly brushing the leaves near the road to remove the particulate matter. This dramatic change on CA shows how effective a layer of particulate matter can be in protecting the leaf from UV degradation as well as blocking photosynthesis and reducing plant growth, stressing the plants and affecting their health and growth over time. There is little difference observed between direct exposure to

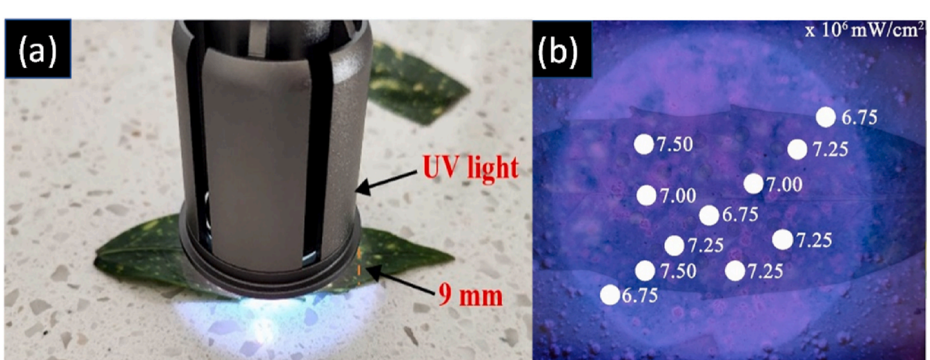

Fig. 7. CAM under UV light: (a) shows the diode laser (λ = 365 nm) positioned above the leaf at a $d \sim 9$ mm, (b) shows the measured irradiance, I (mW/cm^2) at selected points producing an average of (7.1 ± 0.4) x 10^6 mW/cm^2.

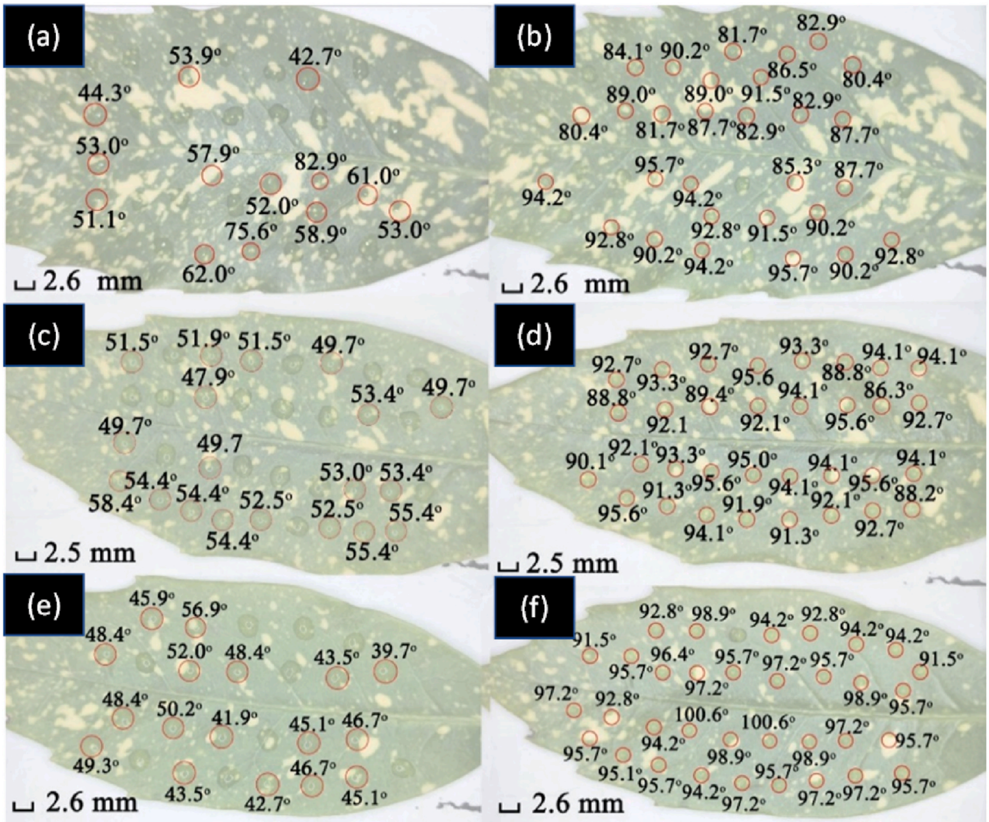

Fig. 8. CAM for three leaves beside the road with heavy traffic (refer to Fig. 3 (d)). LEFT: (a), (c), (e) show calibrated drops on the leaves without brushing, demonstrating a reduction in CA. RIGHT (b), (d), (f) shows the same leaves after gently brushing to remove particulate matter, recovering their hydrophobic properties. Further, note that (a) is for a leaf under direct sunlight whereas (c) & (e) are for leaves near a shaded concrete pillar on the road further along in Fig. 3 (d).

sunlight and shade because the plant is coated with particulate matter. That in turn is an indication of an unhealthy environment for humans and methods so processes to mitigate pollution generation can be warranted, including direct detection of culprit vehicles without exhaust filters.

3.3. *Other plant parameters for future work*

Plants contrast with other organic agents by being a fixed-point sensor - they are generally not mobile and therefore useful in assessing environments. Performing as they function and live, they possess a wide range of sensory properties that can be exploited. Plants have long been known to be sensitive to environmental toxins, water impurities, and pollutants [100,101]. As far back as 1952, for example, the effect of atmospheric hydrogen fluoride on agricultural crops was described [102]. In 1958, ten plant varieties were used to assess sulfur dioxide in the Tennessee Valley, United States [103]. In a few cases, a plant may detect more than one toxic agent simultaneously. Symptoms of ozone and oxidant or of ozone and sulfur dioxide may occur on the same pinto bean leaf when plants are fumigated with either of these pairs of fumigants simultaneously [104].

A few are well-known to gardeners and farmers who use these to check the health of their plants and crops and similarly, others have forensically analysed environmental foliage to assess industrial impacts. To quantify plant responses and identify particular pollutants, samples need to be collected, transported, and analysed in laboratories. For industrial analysis, properties such as chlorophyll content and its degradation, the presence of other pigments, relative water content, and extracted leaf pH are measured directly [105] and often compared with previous studies exposing samples to specific agents, a tedious forensic process. Ensuring identical standards and referencing between sites and measurements extends the challenge. As was noted with laboratory-based contact angle side measurements, this approach to environmental monitoring is time consuming and extremely difficult to build up sufficient data to have reliable and meaningful interpretations of environmental impact. It can be made more difficult because the circumstances in which flowers are bred also influence final observations and interpretations - hydrangeas may be growing with acidic water, predetermining some of the pigmentation to make them blue, before they are transferred to an environment that might otherwise be exposed to neutral or mildly basic water where a white or pink colour might be expected over time. Understanding the sensor history is akin to understanding the fabrication environment. The *b*-IoT will addresses this shortcoming by requiring automated and real or near-time measurements into the cloud at its core, including single referencing benchmarks which can be standardised and automated online for equal global access anywhere anytime. This overcomes the variations that exist with individual measurements by identifying their origins or their likely relevance, much the same way as has been suggested for pandemic assessment in the future. Remote monitoring and mass, or swarm, data accumulation will make this approach to industrial and environmental sensing feasible for the first time. It therefore becomes important to revisit this field and focus on early parameters that might be easier to implement into the internet.

Of the various parameters that can be immediately applied, optical colour change is perhaps the most obvious given there are many low-cost colorimetric sensors that can be coupled to the plants. In many plants this is strongly connected to pigmentation, much of which is related to organic carotene derivatives and various anthocyans. In the case of Aucuba Japonica the yellow pigmentation colouring makes up for a decrease in chloroplasts and therefore chlorophyll. Its presence indicates greater sensitivity to sunlight and from a crude deductive assessment could be used to determine if the plant has been in shade or not over time or used as a UV sensor. Importantly, these colour changes across various plant species are sensitive to soil changes, collectively assessing a change in pH and the presence of impurities that can be exploited. That colour change is explained through metallisation of the pigments - whilst details in many cases are not always understood, soil pH changes the dissolution of metal ions and therefore the quantity that can enter a plant. This metallization leads to spectral changes in pigment response which give rise to colour changes in the plant leaves, petals, or sepals. Aluminium is common in soil and readily soluble and can play a wide role, raising soil toxicity for many species when dissolved in acidic environments [106]. This can be a problem for agricultural products such as wheat, but it can also be exploited by horticulturalist to change flower colours. For example, the blue leaves of the sepal of hydrangea is due to a metal complex composed of anthocyanin, 3-*O*-glucosyldelphinidin, 5-*O*-acylquinic acids, and Al^{3+}, which are assembled through weak bonds that support the metal complex and hydrophobic interactions [107]. Rather than poison the plant, the attachment of Al^{3+} shifts the pigment spectral properties to convert the reddish colour towards blue.

Fig. 9 illustrates the changes that occur because of water pH. What is remarkable is the consistency of such an approach and its exploitation for purely visual aesthetics. On the other hand, in addition to greening and adding beauty to an area, the growth of such plants can reveal information about the environment - shown in Fig. 9 are three images from around the world, from Russia to the UK to Peru, where hydrangeas are remarkably similar in colour, all suggesting the local water used to care for these plants, whether naturally from rain or from human gardening, is neutral to basic, consistent with drinking water. Similarly, this forensic approach can be applied for beneficial purposes. For example, planting seedlings of hydrangeas near industrial sites, including nuclear power plants that may discharge contaminated water into local riverbeds, provides a novel way to assess impact. The elucidation of the mechanisms behind these changes is providing new insight into fundamental material chemistry and therefore creating new approaches to sensing and colour engineering. It follows that simple colourimetric sensors could be integrated with the hydrangea, or other plants, to transmit colour changes fibrelessly via developing transducers to an optical fibre nearby. This can remotely assess pH near a chemical site of concern where the plants are grown. In parallel the greening, aesthetic nature of the plants and their positive effect on the climate and human wellness helps improve many often sterile sites and the livability of a site. The recent pandemic has shown that proactive livability, a term that is becoming more widely accepted, has become crucial for future construction and real estate so that dense human populations can enjoy an environment that does not impact health [108]. This ranges from inorganic surface treatments, smart functional cement materials, including the integration of organic exoskeletons such as diatoms [109] that can support diffusive anti-viral agents, and the use of short wavelength < 240 nm UV light in buildings and aircraft to help reduce transmission of pathogens [110,111]. Plants are also a natural filter for pathogens, potentially useful for indoor environments [112], and combined with the *b*-IoT can offer additional, novel routes to improving livability. They can not only detect and monitor environmental and pollution aspects described in this paper but also potentially pathogens themselves, reporting back into a medical IoT [11] that is also part of the *b*-IoT.

Colour change is a directly observable parameter and pH a quantity of great relevance in many sectors. A novel use of a plant's pH sensing properties has been the extraction of the responsible pigments that are aqueous to determine milk pH and the role of pH in determining milk platelet concentration [113]. Equally important to chemical colour changes where pigment spectral properties are altered through interactions with the environment, plants also possess structural colour. These colours are produced by interferences of light interacting with nanoscale structures, often in specular reflection or in transmission. In plants, multilayer reflectors acting like diffraction gratings can be built from the cell wall or cuticle itself or produced within specialised plastids which are themselves aligned parallel to the cell surface [114,115]. For example, blue iridescence in shade-dwelling Begonias originates from iridoplasts [115], modified chloroplasts in which the grana are stacked three by three and where thylakoids membrane-bound compartments inside the chloroplasts, are highly reduced. Plant structure need not be ordered generally but at specific wavelength regions may appear to be so, leading to selective scattering, a form of Anderson localization that can be exploited. They can occur in the leaves, flowers, or fruit.

An interesting example are Bouligan structures made of cellulose fibrils helical in nature, that occur in some plants suggesting convergent evolution with those appearing in some insects [116]. The fruit endocarp of Margaritaria nobilis iridesces by reflection of light from the Bouligan structures in the cell walls - this potentially chiral iridescence can appear to change colour if the fruit has layer of water or potentially other solvent since the effective index of the periodic structure determines the spectral region reflected. Although by colour we

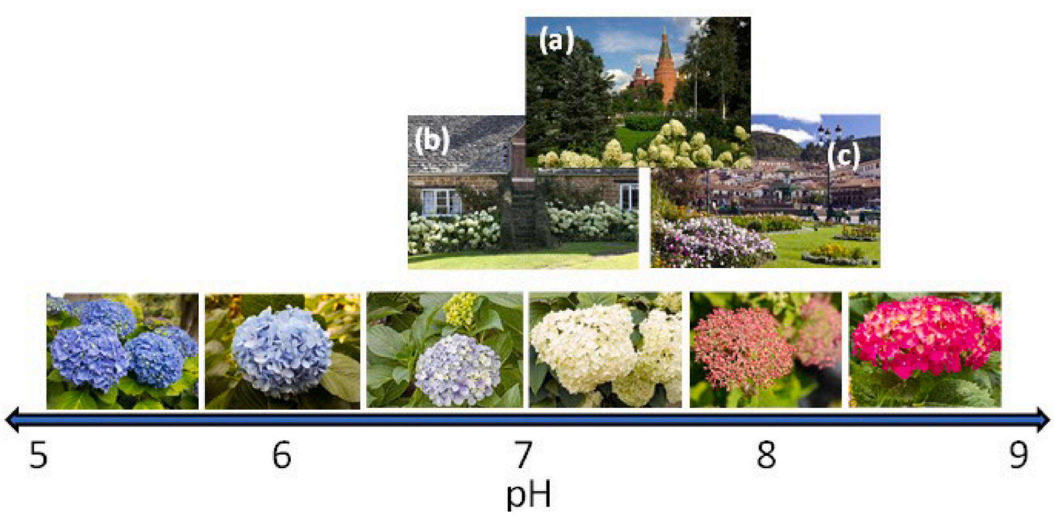

Fig. 9. Hydrangeas colour reflects the water pH used to raise and treat them. Acidic water produces bluer leaves whilst basic water produces red. By examining photographs of hydrangeas from various places an assessment of water quality can in principle be made. For example, the hydrangeas from (a) Moscow, (b) Worcestshire UK and (c) Cusco Peru suggest the water being used is slightly basic between 5.5 and 8.5, possibly local drinking water. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

traditionally imply visible light, it goes without saying that direct specular reflection from plant surfaces in non-visible wavelength regions also plays an important role. Recent work demonstrates that plants exploit near UV scatter to attract bees and not flies to their flowers for pollination purposes [117]. The challenge for pigments is that organic molecules tend to have a UV band edge that limits any decrease into the deeper UV, a gap that structural colour can in principle fill. The utilization of fibreless, or wireless, at longer wavelengths towards the near infrared, infrared (6G), terahertz (5 & 6G), mm (5G), microwave and RF regimes can provide additional useful information from plant sensors. Structural reflectors bypass chemical absorption and are particularly sensitive to strain changes that alter the period (where the leaf is stretched, bent or shrinks) or index changes that alter the effective index providing information about the environment and therefore the wavelength regimes scattered. At longer wavelengths, they can be used to assess thermal conditions as well as monitor deeper into the plant itself.

Another important feature about organisms (such as the platypus) and plants is their electrical conductivity and reception to electromagnetic fields, the very thing that raises interesting perspectives on future fibreless monitoring on health. Electroreceptive structures bypass colour altogether. For example, changes in reflection or scatter of terahertz wavelengths have been used for remote monitoring of water content in grapevines to assess their condition [118] as well as determining the distribution of some constituents within plants [119]. It has not been used to assess the impact on the state of water within the plants cellular structure, a tremendous research opportunity directly correlated with nutrient uptake and plant health. This direction has the potential of generating more meaningful measures of health testing of fibreless technologies such as 5G, 6G and whatever the future brings. The use of 5G in communications and future vehicles (that may soon drive along the Shanghai road where the samples reviewed here were obtained) can be combined with any other methods within the *b*-IoT to not only assist the technology but to perform routine health diagnostics across a population.

4. Conclusions

The assessment undertaken for Aucuba Japonica as a plant sensor via its changes in surface wettability indicate a novel approach to environmental and pollution monitoring, opening a new direction of research. The use of a field portable, packaged smartphone CA analyser is transformative for wettability measurements more generally. Although more work is required to develop working protocols directly into the field, the instrument already enables much closer real time measurements close to the field. The top-down measurements offer comparable performance without the degree of instrument concern. This offers a convenient, reliable way to measure surface wettability on-site using readily accessible and existing consumer grade technology. In addition, the top-down approach allows an entire surface to be mapped, generating data which allows more confident assessments of contact angles and their error distribution across a plant, an advantage of scaled data which becomes amenable to machine learning and other approaches to further refine their accuracy and reliability. With the advent of increasingly sophisticated machine learning and AI, as well as rapid computational times, direct numerical processing of drop images that fall outside of the spherical caplet approximation, such as rain drops, offers a way of remote automation. The translation of a smart IoT tool into the field will enable reliable measurement and mapping of properties of leaves in near real-time, illustrating the value of plants as intrinsic environmental sensors. For botanists, this technology presents a scientific disruption enabling large data generation that can provide reliable, taxonomic information about plant evolution and the environment it is in. The same principles can be applied to other measurements as indicated in the previous section. The *b*-IoT can decouple from laboratory measurements or integrate them as required.

What has become clear in this work is the need to understand both organic and inorganic materials and material systems - this spans across the entirety of the IoT for the bionic-IoT to offer meaningful benefit. This is because at present little of the IoT is sustainable and the impact on society from both livability and health has not been properly assessed. A number of examples spanning the network were given. Plants themselves are made of complex systems that give rise to sensitivity to the environment through changes in mechanical density, flexibility, pigmentation and lighting colour and moisture. But natural systems offer an unprecedented richness and with the power of combined systems and sensors can greatly expand the IoT. In addition to contact angle, pigmentation is sensitive to impurities, a more obvious example of how plants can be used directly to monitor industrial and city street toxins. The environment impacts the entire system in many ways, which are still to be fathomed, and so there remains the potential for many new alternative routes to seed and "grow" the *b*-IoT.

Beyond botany, combining smartphones with natural plant sensors is a hybrid technology that opens a novel approach to environmental monitoring including for climate change, the basis of a bionic internet-of-things, or *b*-IoT. Here, specifically, the use of Aucuba Japonica, a robust plant that has wide regional distribution near optical fibre hub clusters, has been characterised and significant changes in parameters were detected that make such bionic sensor networks feasible. Across smart cities, existing botanical gardens can be transformed into major sensor hubs in the first instance. The application to pollution measurements was demonstrated. Highly sensitive detection of particulate matter deposited by the environment on the leaf offers a large dynamic sensor range. The long-term performance of the sensors compares favourably with the need for continual maintenance required with electronic versions - maintenance of gardens is already commonplace and the technology posited here adapts into that. To improve accuracy and reliability over longer time periods, the changes arising from aging and impact need to be understood and calibrated. The role of UV exposure in aging the sensors was explored and confirmed, providing a novel tool for recording and tracking solar measurements over time, and consequently their impact on local climate changes and what measures local citizens need to adopt. Degradation of the protective waxy layer occurs before the plant itself is exposed and destroyed. It was found that under the leaves, which do not require access to the sun and are less exposed, the cuticle layer is likely to be much thinner and therefore, removal is faster where the epidermal and cell layers burn earlier. The conjecture on different thicknesses at the top and bottom of the leaves, as the results point towards, is supported by existing literature that has measured this [95], confirming the validity of the measurements. In fact, the difference in layers is, through strain and thermal expansion analogous to thin film layers [120], partly responsible for the way leaves turn outwards to collect sunlight, effectively a multilayer thin film stress effect supported by water infill.

This form of bionic instrumentation is particularly attractive because it couples low cost, low maintenance, aesthetically pleasing and naturally growing sensors with smartphone diagnostics. In principle, other technologies could be integrated into the *b*-IoT, including for example, bionic jellyfish or scorpion skins which mimic natural organisms [121, 122]. Here, we directly integrate living organisms though in principle the *b*-IoT can use both. They blend into an environment, creating aesthetic, health, and wellness improvements for people and animals, a feature that contrasts strongly with current IoT sensor technologies and networks. Aucuba Japonica is one example that is regionally widespread offering a sensing tool that can be used to map responses across the globe, all collated at one point or distributed for wider access. There are many, many plant and animal sensing regimes that can also be integrated with the most disruptive realisation being multiple capability that further strengthens accuracy, forensic determinations, and reliability. Through the internet, the sensors data from each plant can be brought together so that mapping across regions where potentially thousands of routine measurements are taken in near real-time - a multitude of sensor types in a multitude of numbers. They are linked through the same cloud diagnostics into which each edge component or computer communicates. A smart tool such as a contact angle analyser on a phone means that this technology is widely accessible to the consumer, perfect for citizen engagement in a networked super diagnostic for environmental monitoring and, by extension, potentially for climate change analysis. The totality of the integrated plant-internet system marks a first step towards a *b*-IoT, a crucial technology development that can directly monitor environmental impact through several causes, including natural and human-induced impact. It can potentially expand the scope of tools in the assessment of climate change more broadly whilst simultaneously enhancing human health and wellbeing. Finally, it is worth noting that much of the signal processing and sensing within plants has a quantum mechanical aspect involving photon excitation and electron transfer and tunneling raising the possibility that computational aspirations may one day draw on plant and organism physics to resolve current quantum deployment challenges and to do so on a global scale.

CRediT authorship contribution statement

John Canning: Conceptualization, Supervision, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing. **Yunlong Guo:** Data curation, Formal analysis, Investigation, Project administration, Validation. **Zenon Chaczko:** Supervision, Investigation, Methodology, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yunlong Guo reports financial support was provided by Australian Government Department of Education Skills and Employment.

Data availability

Data is contained in the images but can be provided on request.

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