The cognate plant

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Plants have evolved various ways to respond to stimuli (irritability) which are less movement-intensive. The earlier observations on irritability were explained using the laws of physics and natural science. With the progress of various 'omics' tools, the irritability of plants is now being elucidated in the light of genes, small RNA molecules and various other signal molecules like peptides, lipids and phytohormones. This science has now become more sophisticated into plant neurobiology with parallels being drawn from animal neurotransmitters, synapses, brain and cognition. Here we discuss the advent and prospects of plant neurobiology.

Plant irritability: observations of the visionaries

Limited by their sessile nature, plants have evolved diverse types of ingenious developmental and metabolic behaviour to comply with their environment. The collective term for such behaviour is irritability. The first documented observations of this phenomenon come from one of Charles Darwin's[1] lesser-known works in which he proposed that the tip of the radicle (embryonic plant root) directs the movement and function of adjoining cells, much like the brain of lower animals. Understanding of the 'plant brain' was further enhanced 33 years later in 1913 when Bose[2] published his revolutionary monograph. With his indigenously designed resonant recorder, electric probe and the crescograph, Bose elucidated that almost all responses to irritability in animals had a counterpart in plants and manifested as long-range electrical signals throughout the plant body. He was the first to coin the term 'plant nerve'. The findings of both these visionary scientists' work reflected the idea that plants are intelligent beings, and are capable of acquiring and storing information from their surroundings and can retrieve the data when required. These radical propositions were poorly received by the then prevalent Victorian philosophies of science. Later in 1984, McClintock[3] emphasized the idea of a 'thoughtful cell' in her Nobel Prize acceptance speech. Since then, gradually the study of plant intelligence has come into prominence as 'plant neurobiology'.

What is plant neurobiology

The new field of research in plant neurobiology as proposed by Volkenburgh and co-workers[4] has initiated debates within the scientific community. Plant neurobiology studies irritability as the integration of molecular, chemical, hormonal, genetic and electrical components of plant signalling and elucidates the infrastructure of information network within the plant and the surveillance system that plants use to communicate with their outer environment. These plant signals include electrical impulses, phytohormones, intercellularly transported macromolecules, peptides and many other yet-to-be discovered molecules. This new discipline is a combination of plant physiology, molecular biology, all the different 'omics' and ecology leading all the way up to systems biology. Plant neurobiology uses metaphors, images and ideas from animal physiology and tries to draw a parallel between plants and animals as far as neurones, synapses, brains, intelligence and cognition are concerned.

Intelligence versus cognition

Intelligence is defined as the capability to reason, plan, solve problems, think abstractly, comprehend complex ideas and learn from experience. It is a quantitative aspect that varies in degree in the living world from individual to individual. Cognition, on the other hand, is the act of acquiring and categorizing knowledge, storing it in memory, making judgements and computing how to react in different situations retrieving specific memory from the embedded databases within our systems. Both intelligence and cognition as described above are typical of higher animals, especially primates and humans. The antagonists of the 'plant neurobiology' phenomenon naturally questioned whether plants are capable of learning, memorizing, computing and communicating (both in a friendly and un-friendly manner). Have plants also evolved as cognate beings? The protagonists of plant cognition have since come up with various exciting findings.

Learning, memory and plant computing

Gagliano *et al.*[5,6] have proposed that plants are capable of associative learning. They found that pea seedlings could associate the best direction for growth with the occurrence of light and that a repeatedly dropped mimosa plant 'learnt' not to curl up its leaves. Molinier *et al.*[7] reported that UV radiation-treated seedlings of *Arabidopsis thaliana* showed an increase in somatic homologous recombination of a transgenic reporter, which persisted in subsequent untreated generations like a transgenerational memory of stress. Engel[8] has shown that plants use the principle of quantum computing to achieve efficiency during photosynthesis, where solar energy is transformed into carbohydrates in one million billionth of a second. Peak *et al.*[9] found that *Xanthium* leaves regulate their uptake of CO_2 by 'distributed computation', which involves information processing via communication between many interacting stomata which are distributed in patches of either being closed or open. These patches of stomata are found in specific patterns that sometimes move around a leaf at a constant speed. The stomata act like simple computers and respond to the actions of their neighbouring stomata.

Network chemistry and communication systems of plants

Plants are social beings and can differentiate between kin and strangers. They form communities and associations like symbiosis, mutualism, commensalism and parasitism with other organisms, especially microbes. Plants are well connected to each other via sophisticated chemical networks produced by their roots and the mycelia of the associated mycorrhizal fungi. This 'internet' of plant roots, fungi and other microorganisms forms an 'information superhighway' connecting different species of plants in a 'web'[10]. *Cakile edentula*, a member of Brassicaceae, can identify other members of its species and does not compete with them for resources. This plant reorients its leaves horizontally and vertically in a shade-avoidance reaction among kin neighbours to decrease mutual shading and increase fitness. Perception of vertical red/far-red light and blue light profiles is considered to be responsible for this phenomenon. Disruption of light patterns and mutations of *phytochrome B*, *cryptochrome* 1 or 2, or *phototropin* 1 or 2 photoreceptor genes or *tryptophan amino-transferase of arabidopsis* 1 gene required for auxin synthesis can impair such responses[11,12]. Certain invasive plants can defend their territory by releasing allelochemicals that kill native grasses. On the other hand, oxalic acid secreted by the roots of *Lupinus* sp. protects the host plant as well as other neighbouring flora from the allelochemicals of invasive plant[13]. Elhakeem *et al.*[14] proposed that brief disturbances above ground could lead to changes in underground communication that cause nearby plants to alter their growth strategies. The chemical network between microbes of the phyllosphere, the endophytes and microbes of the rhizosphere is like the second brain of the plant body which participates actively in plant metabolism and defence processes.

Interkingdom messaging by plants

The biochemical and genetic mechanisms of interaction between the host plant and its rhizophoric, phyllophoric and endophytic microbiomes have just begun to be understood in recent years[15]. Many plants successfully manipulate animals for pollination (e.g. *Raflessia arnoldii* has flowers with odour of rotten flesh) and self-defence (e.g. chemical distress signals emitted by corn infested by caterpillars are picked up by wasps that predate on caterpillars). Flowering plants produce tannins and allergens that prevent animals and humans from overgrazing during flowering. The same plants then produce delicious fruits that lure animals and humans into picking, transporting and eating them, thus helping in seed dispersal. Carnivorous plants like *Nepenthes* have developed a means to attract their prey using methods to trap, kill, digest and absorb the victims. In tune with the 'Gaia hypothesis'[16], plants are organisms that interact with their surroundings on earth to form a synergistic, self-regulating, complex system that helps maintain and perpetuate the conditions for life on this planet. Plants 'catch on' situations, 'make sense' of things and 'figure out' what to do. Such 'cognitive abilities' of plants leads us to the question of location of the plant brain and its architecture of neurons, synapses and neurotransmitters.

The brainy tip

The root tips are the most active component of the rhizosphere. As pointed out earlier by Darwin, scientists now speculate that the 'plant brain' is located within the transition zone of the root tip[17]. It is here that various info chemicals are released and absorbed, which facilitate plant-to-plant and inter-kingdom signalling. Scientists are also of the opinion that 'plant synapses' have evolved together with the vascular system and the polar auxin transport machinery. Synaptic communications are made through the signal-mediated release of auxin into the synaptic space between two adjacent cells connected via a synaptic cell–cell adhesion domain[18].

Parallels of animal neurotransmitters in the plant world

Scientists have proved that *Arabidopsis* cells express huge sets of neuronal molecules that support endocytosis, vesicle trafficking and regulated secretion which in turn fuels cell–cell communication. Acetylcholine, catecholamines, histamines, serotonin, dopamine, melatonin, GABA (g-aminobutyric acid) and glutamate, all metabolic neurotransmitters of the animal nervous system are also found in plants, often at higher concentrations[19]. Genes similar to that of the glutamate receptors in the animal nervous system have been found in plants and GABA has been implicated as a maternal signal that determines the direction of pollen tube towards the ovule. Genes of acetylcholine esterase have been cloned from maize. Serotonin and melatonin are said to play roles in plant development and flowering. However, the most important and well-studied plant signal molecule is the phytohormone auxin that mediates the activation of transcriptional regulators cascading into changes in gene expression. Secreted auxin molecules interact with cell-wall peroxidases to form reactive oxygen species (ROS) which are highly potent signalling molecules in plants[20].

The way ahead

A century ago, Bose pointed out that similarities in responses of animals and plants are of evolutionary significance. He emphasized that analysis of plant systems is fundamentally important, as they can be used to elucidate animal irritability phenomenon. The fact that plants have a consciousness that can be blocked by anaesthesia had been proved by Bose[2]. Similar results are now being reiterated in recent studies[21], where anaesthetics have blocked action potentials, endocytic vesicle recycling and ROS homeostasis. The evolutionary history of land plants is skewed towards increased sophistication of plant behaviour[22]. Cognitive-like traits have evolved in plants as a means of communication with self and non-self. The idea of whether we can regard this cognition as consciousness is controversial, but it is gradually being accepted within the scientific community. Hemachandran *et al.*[23] have pointed out that although the precise mechanism of plant communication has not yet been deduced, continued effort using interdisciplinary science and engineering is required for a deeper understanding of plant intelligence and communication for better elucidation of agricultural and ecological systems. In 2013, Calvo[24] had developed a new subject called 'philosophy of plant neurobiology'. This innovative field of research is an amalgamation of the philosophy of cognitive science and plant neurobiology. It is so nascent that researchers have just begun to create a vocabulary for the same. Once the molecular lingua franca of plant intelligence is deciphered, the ecological significance of plant metabolism, reproduction and disease resistance can be better understood. Recently, optimization algorithms based on plant intelligence have been used to solve benchmark vehicle routing problems[25]. Moreover, symbiotic robot-plant bio-hybrids are being developed to form an interactive interface between humans and plants for the study of plant growth. Such technologies can be used by breeders in future to provide nutrients according to the needs of plants and to develop suitable ideotype for any crop[26]. Meanwhile, we have enough opportunity to ponder upon whether cereals, pulses, vegetables and fruits let out a ‘silent scream’ every time we use them for our daily meals.

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In praise of agnosticism

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In this note, we portray agnosticism as a line of positive thinking and emphasize that it is in conformity with science and mathematics.

The origin of the notion of God and religious beliefs can be attributed to the attempt of the primitive people to come in terms with the hostile environment they were exposed to. They could not comprehend and were awed at the different physical phenomena like alteration of day and night, lightning, thunder, flood, storm, eclipses, death, etc. They soon realized their helplessness and defencelessness against the forces of nature. They hypothesized that there must be some supreme power or deity/deities that controls all these happenings. They thought these deities need to be pleased to avoid incurring their wrath. So they imagined these deities in different forms, depending on the nature of the force they represent, and started worshiping them. Thus submission/surrender to the hypothesized Supreme Being is the foundation of all religions. With the progress of time and growth of knowledge our view of the universe has changed drastically, but fear of the unknown and search for reality continues. Sages and philosophers contemplated on this issue and thus there emerged the notion of divinely inspired or revealed knowledge resulting in what are called ‘dharma sashtras’ or religious scriptures. Based on such revealed knowledge there emerged different schools of thought. Consequently, our philosophy of religion developed and we now have sophisticated terminology like ‘search for the ultimate reality’, ‘communion with the Supreme Being’, ‘to merge with the Supreme Soul’, etc. A glimpse of any old civilization shows that the worship of some deity was an integral part of its culture. However, parallel to these religious thoughts, there also emerged other views unwilling to accept the control, power or even the very existence of a Supreme Being. These systems of thought go by the name atheism and agnosticism.

The term ‘agnostic’ was coined by the English biologist T. H. Huxley