OUR UNDERGRADUATE BOTANY CURRICULUM NEEDS MORE EMPHASIS ON PHYSICS AND PHYSICAL LAWS

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Study of life sciences in recent times has become more quantitative as well as integrative in nature. The subject of Physics has a prominent role in the interdisciplinary learning process as physical laws, principles and concepts form the basis of all natural phenomena. Physics encompasses the studies that deal with the various forces and mathematical constants from which we derive useful theories. It is difficult to understand the root laws of any specialty science including botany without the study of those forces, and the equations that measure the relationships between mass, energy, pressure, volume, or experimentation using these fundamental relationships.

Botany (or plant biology) is the study of a plant that is basically a self replicating chemical system. Chemistry is the interaction of atoms and all such interactions are ultimately governed by quantum mechanics. Plants, like other forms of life, are complicated objects constructed of various biological materials. These different biological materials have physical properties in the same way that non-living objects have physical properties. The physical form of life, working with its available biological materials, must be appropriate to survive in the physical environment. Unfortunately such introductory discussions are rarely held in the undergraduate botany classes.

Precisely speaking, every aspect in botany (both structural and functional) involves physics and physical laws. The basic concept of physics is energy that means capacity to produce work. The way water is drawn up through plant roots; the way soil nutrients dissolve in the water for the plant; the way the plant's DNA controls cell division and other metabolic processes; the way plant pollen is carried in the wind to another plant, the way chemicals in a flower give it a bright colour and so on are the examples of different kinds of work, a plant performs. All these diverse works entail different physical laws.

At the undergraduate level, two thirds of botany curriculum, by and large, deals with describing the form - size, volume and mass of the specified structure. The rest of the curriculum describes their functions *in situ* without giving much emphasis on their interaction or energy exchange with the surroundings. Failing to understand this valuable point gives a lopsided idea to the students who often find difficulty at the advanced level of study and thinking. Comparisons between how a biological feature varies with predictions made by the laws of physics can offer explanatory power, testable hypotheses and guidance toward important open questions in biology. For example, for a robust foundation to understand the diversity in plants and the organs of which they are composed of, energy minimization or optimization could be assumed as the selective force shaping the evolution of internal and external plant surface areas and morphology. For instance, many vascular plants vary in size sometimes by nearly twelve orders of magnitude as it grows from a seedling to a mature tree (eg. Sequoia plant). Cellular processes in such large vascular plants are limited by the rate at which networks of vascular tissues can supply energy and other essential resources. The phloem system facilitates transport of energy-rich sugar and signaling molecules in plants, thus permitting long-range communication within the organism and growth of non-photosynthesizing organs such as roots and many kinds of fruits. The resource distribution networks are assumed to have three fundamental properties: first, they branch to reach all parts of the plant; second, the resistance and fluid flow per conducting tube are independent of the total path length and plant size thus the transport energy required for distribution is optimized; and

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third, the terminal units (e.g. petioles, fruits, root tips) do not vary with body size. The phloem is an intricate distribution system and the size of this conductive element obeys the universal power rule ($Y = ax^b$). Recently key insights have arisen from an increased understanding of how the properties of distributive vessel networks influence whole plant metabolic and physiological traits[1,7].

Size of a plant is so fundamental that it influences nearly all structural, functional, and ecological characteristics, from rates of functional processes within cells to abundances of species in ecological communities. More of the intra-class evolution of plants has been linked to body size than to any other characteristic. Adult body size exerts a quantitative dominance over how a species lives and for how long and on its rate of living and extraction of resources from its environment, and consequently on how many of its kind can live simultaneously on a unit of habitat. These size dependent relationships give a marvelous basis for understanding ecology and predicting conservation outcomes.

Surprisingly, the idea of scaling relationships (Allometry, study of the relative growth of a part in relation to an entire organism) or its consequences is generally not provided to the students before dealing with plant morphology, taxonomy and ecology, though the 'square-cube law' as the basic mathematical principle applicable to a variety of scientific fields is as old as of fifteenth century[2]. After Galileo's early strides toward understanding how geometry and size affect the mechanical soundness of structures, the method of dimensional analysis emerged to find utility in biomechanics (form and function), physiology (metabolic), genetics (genomics) followed by a broad expansion into embryology and development, evolution and ecology[3]. The surface area to volume ratio can be important in determining the rates of chemical reactions as well. For example, reaction rates are increased by increasing surface area to mass ratio by breaking large molecules (polymers) into smaller molecules (monomers), then molecules to atoms, the overall surface area available for reaction increases.

The analysis of scaling requires: first, measuring how a biological characteristic changes with size; second, understanding some useful properties of logarithms and statistical regression (the observed scaling is typically a simple power law. A power law ($y = ax^b$ or in logarithmic form: $\log y = b (\log x + \log a)$ is a relationship in which a relative change in one quantity gives rise to a proportional relative change in the other quantity, independent of the initial size of those quantities; and third, application of relevant physical laws. To best of my knowledge, these fundamental aspects are not introduced to any botany student at undergraduate level.

Central to the plant functioning is the process of photosynthesis, where light from the sun is converted to chemical energy by the plant. Physics explains how specific photons of light (containing specific amounts of energy) are absorbed by specific plant molecules (the absorption involves changes in electron orbital and energy levels), and then this energy is transferred to other particles and molecules and eventually is stored in the bond energy within sugar molecules. All of this involves lots of physics. All other things being equal, for example, the interception of light and the rate of gas exchange with its external fluid medium is proportional to the ratio of surface area to volume. This can be easily explained by Fick's first law: $J = D_i\ (\Delta C/\Delta x)$, which states that there is a direct dependence of the rate of diffusion (symbolized by dS/dt) on the surface area (symbolized by A) through which diffusion occurs and an inverse dependence of the rate of diffusion on distance (designated by x): $dS/dt = -D_i\ A\ (\Delta C/\Delta x)$. Accordingly the organelle that perform photosynthesis must be small, very flat to reduce x and increase A, this is exactly the shape of a chloroplast. While dealing with the photosynthetic pigment systems, these simple relationships come very handy. Similarly light interception by the leaves can be easily described by extending Beer's law ($A_i = \log_{10} I/I_0$) which is generally taught at the high school level.

The energy transfer process in photosynthesis being the fastest (on the order of 10^{-9}s) and the most sophisticated redox reaction on earth that ensures life's survival is often neglected or described cursorily. The key to the conversion of light energy to chemical energy lies in the higher reduction potential of the excited chlorophyll molecule at the reaction centre. The role of midpoint electron potentials, E_m (in Volt) in electron transfer (mitochondrial/chloroplasts) and free energy released to be convert into ATP requires explaining lucidly and unambiguously.

Describing water and membrane potentials in terms of physical laws is equally important to understand solute (ion) transport within the plant body. It is necessary to note that the flow of ions across a membrane is not only governed by the concentration gradient of the concerned ion but also to their electrical potential difference[4]. All these measurements need a clear idea of specific physical laws. Physical laws and processes are *sine quo non* to understand the growth, survival, and reproduction of plants and also routinely shape the course of plant evolution.

Evolutionary changes can be described in a number of ways; one is to consider each evolutionary change as a *vector* having both *magnitude* and *direction*. The magnitude component – the degree, to which antecedent and descendent conditions differ from one another, reflects the genetic and developmental capacity of a particular type of organism to vary about the modal form within its population or species. The variants are differentially affected by the environment and their survival depends on the way they perform their biological function. The directional component of each vector may be either positive or negative, that is, like or contrasting to the preceding evolutionary changes[5]. It is a function of the nature, intensity, and duration of application of factors within the environment that influence the survival of the variants produced by a particular type of organism. Much of the way some features of the physical environment influence the survival of phenotypes can be predicted because they are governed by physical laws and processes whose operations can be described with the aid of very precise and usually accurate equations. Thus in contrast to our relatively poor state of knowledge concerning the intrinsic capacity of organisms to genetically produce phenotypic variation, we know comparatively much more about how the interactions between phenotypes and their immediate environments influence fitness[8].

Finally, let us consider another vital function of a living plant. Complete and timely replication of the genome is a prerequisite to cell division and growth. The process of DNA replication (genome duplication) for this purpose is generally taught in considerable details. Genome replication originates at random places along the DNA strand, yet replication of the genetic material finishes within a defined time. To solve the fundamental problem of how cells ensure that every last piece of genome is replicated on time, physical models based on phase-transition kinetics in condensed-matter systems may be considered. These models explain how these just-in-time replications may happen[6]. For instance, when the entire tray of water freezes in a freezer, nucleation sites grow to fill the entire volume. The nucleation rate as well as the growth rate is randomly distributed in space and time. Similarly, despite the intrinsic stochasticity of the initiation of DNA replication, cells can still control the amount of time it takes to replicate the genome. However, occasional large gaps may arise to delay the completion of water freezing or DNA duplication. In case of DNA replication, the last coalescent event between the growing replication bubbles determines the duration of DNA replication. For cells to achieve an acceptable distribution of replication completion times, the initiation rate I (t) should increase during replication. Such a model is in direct agreement with extracted values of I (t) from experimental data[6].

Though this may sound little too heavy for the undergraduate students of botany but they can be made aware of the fact that many such fundamental problems of biology can be handled precisely with the aid of interdisciplinary approach. A little introduction to such physical phenomena, as fluid mechanics, electrophysiology, optics etc, at the undergraduate level should help our students to have a stronger base to be more imaginative to research on many unsolved riddles of plant biology.

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