Planta (2022) 255:128
https://doi.org/10.1007/s00425-022-03903-5

REVIEW

Molecular communication network and its applications in crop sciences

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Received: 6 January 2022 / Accepted: 21 April 2022 / Published online: 17 May 2022

Abstract

Main conclusion **Plant molecular biology and bacterial behaviour research in the future could focus on using genetically engineered bacteria as a sensor, hormonal/disease detector, and target gene expression, as well as establishing a bioluminescence feedback communication system.**

Abstract Over the last two decades, understanding plant signal transduction pathways of plant hormones has become an active research field to understand plant behavior better. To accomplish signal transduction, plants use a variety of hormones for inter- and intra-communication, and biotic or abiotic stressors activate those. Signal transduction pathways refer to the use of various communication methods by effectors to elicit a response at the molecular level. Research methodologies such as inter-kingdom signaling have been introduced to study signal transduction and communication pathways, or what we can term plant molecular communication. However, stochastic qualities are inherent in most technologies used to monitor these biological processes. Molecular communication (MC) is a new research topic that uses the natural features of biological organisms to communicate and aims to manipulate their stochastic nature to achieve the desired results. MC is a multidisciplinary research field inspired by the use of molecules to store, spread, and receive information between biological organisms known as "Biological Nanomachines." It has been used to demonstrate how biological entities may be characterised, modelled, and engineered as communication devices in the same manner as traditional communication technologies are. We attempted to link MC and PLANT'S MC in this study and we believe that reasonable combined efforts may be made to use the functional applications of MC for detecting and understanding molecular-level activities such as signaling transduction pathways in crops.

Keywords Plant's molecular communication · Crop biotechnology · Nanomachines · Signal transduction · Signaling transduction pathways · Information molecules

Communicated by Gerhard Leubner.

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Introduction

Plant hormones serve as signaling molecules, controlling molecular activity in specific cells, and transporting it to other plant parts. They also promote leaf shedding, fruit growth, ripening, and the formation of roots, stem, leaf, and flowers. They affect the tissues that expand upward and downward and the death of plants. Further, plant hormones play essential roles in developmental, growth, and stress-related responses. Over the last two decades, extensive research has been conducted using molecular, biochemical, and physiological methods, especially to enhance crop quality and quantity and understand their hormonal intervention and increased stress tolerance.

Stresses, both biotic and abiotic, usually occur concurrently in nature and include a variety of factors ranging from flooding to drought, freezing to heat, photosynthesis, toxicity, nutrient deficiency, and damage caused by predators and pathogens. Because of their inherent ability to sense the environment, all these factors cause plants to exhibit a particular behavior to respond to and resist these changes: the ability to adjust their speed of growth in accordance with the surrounding plants (Ballaré and Casal 2000), the production and sensation of volatile smells, e.g., in case of insect attack (Yoneya and Takabayashi 2014), and preparation for the defense in response to such potential threats (Karban et al. 2006), and their adjustment according to the gravitational force and feel of wind and touch (Braam 2005). These lead to a biosensory network in plants governed and interceded by a complicated signaling network. Signaling, sometimes referred to as a sign in literature, involves the production of different kinds of molecules for communication and initiation of different processes at the molecular level within and in the surroundings of a plant. In each type of stress, plants behave differently. The response against biotic stress is primarily mediated by ethylene, salicylic acid, and jasmonic acid, whereas abscisic aid (ABA) usually defends against abiotic stress, germination, and the development of the seed.

Different detection techniques have been developed, including surface-enhanced Raman spectroscopy (SERS) (Ogundare and Van Zyl 2019), laser-induced breakdown spectroscopy (LIBS) (Nicolodelli et al. 2019), and localized surface plasmon resonance (Wang et al. 2017), to study plant diseases, the effect of chemical sprays, and the detection/behavior of plant hormones and their role in plant growth and analysis of plant leaves, stems, tubers, roots, grains, seeds, and fruits.

We discuss molecular communication (MC) (Akyildiz et al. 2008; Suda and Nakano 2018; Moore et al. 2006), an evolving research field that uses molecules as information carriers and defines biological processes as a communication network like traditional communication. It uses a biochemical mechanism to synthesize, emit, accumulate, and transform cellular responses (Akan et al. 2016; Akyildiz et al. 2011). This natural phenomenon leads to the use of chemicals as signaling. Since molecular communication (MC) uses biologically compatible signals, significantly less energy will be required to generate and propagate such signals. Properties like biocompatibility and low power consumption make signaling using chemicals appropriate for such applications in which it is not feasible or not desirable to use electromagnetic signals. From the information and communication point of view, understanding molecular signaling among living cells provides an understanding of the traditional communication-based fundamentals of natural organisms, as well as a way forward for the development of innovative nano networking skills that can be used for agricultural research and development, as this field is a little new to crop biotechnology.

The MC research is motivated by the communication of natural cells. The synthesis, emission, selection, and conversion of information-carrying molecules to cellular responses are studied via biochemical processes due to their inherent viability for biocompatible environments. Each single biological entity is defined as a nanomachine. A signal transduction mechanism of MC that makes it possible to control and engineer the stochastic behavior of biological entities is based on information molecules that flow between biological nanomachines as a signal. The biological entities or nanomachines, when combined, comprise a network called molecular communication network. Research is being carried out to utilize the features of MC networks parallel to traditional communication networking technologies. A comparison of conventional and molecular communication network technologies is compared in Table 1 for better understanding.

This network of biological nanomachines in Fig. 1 can be subdivided into (i) a transmitter portion that encodes information into information molecules; (ii) adding information molecules to the carrier or emitting molecules in the medium; (iii) propagating information molecules; (iv) obtaining information; and (v) decoding information into chemical reactions or data storage, etc. This architecture can also include transport molecules to take information molecules, guiding molecules to guide transport molecules, interface molecules to allow a transport molecule to transport information molecules precisely, and addressing molecules (not shown in the figure) to decide the bio-nanomachine receiver (Nakano et al. 2012).

Whereas in "Comparison of signal transduction in molecular communication network and plants" we describes plant signal transduction by taking an example of ABA signaling and then discusses the signal transduction techniques used by MC networks. The next section addresses how the idea

Table 1 Feature-based comparison of molecular nano-networks and traditional communication networks

Features of communication	Molecules-based nano-networks	Traditional communication networks
Encoding	Concentration, i.e., number of molecules per unit volume	Time-varying sequences transport information
	Change in chemical structure or polarization	Encryption
	DNA sequencing	Encryption
Propagation	Physical transportation or diffusion under external environmental conditions	EM Waves or Acoustic waves (with the speed of light), light
Noise	The overlapping concentration of molecules	Overlapping of undesired signals with information
	The undesired reaction between information molecules and environmental molecules	
Transmission of data	Chemical states and process	Text, voice, or video
Reception	Chemically driven processes	Data in bits
Power	Low power requirements	High power requirements
Information type	Molecules	Bits
Medium	Aqueous or gaseous	Air, copper, fiber optic

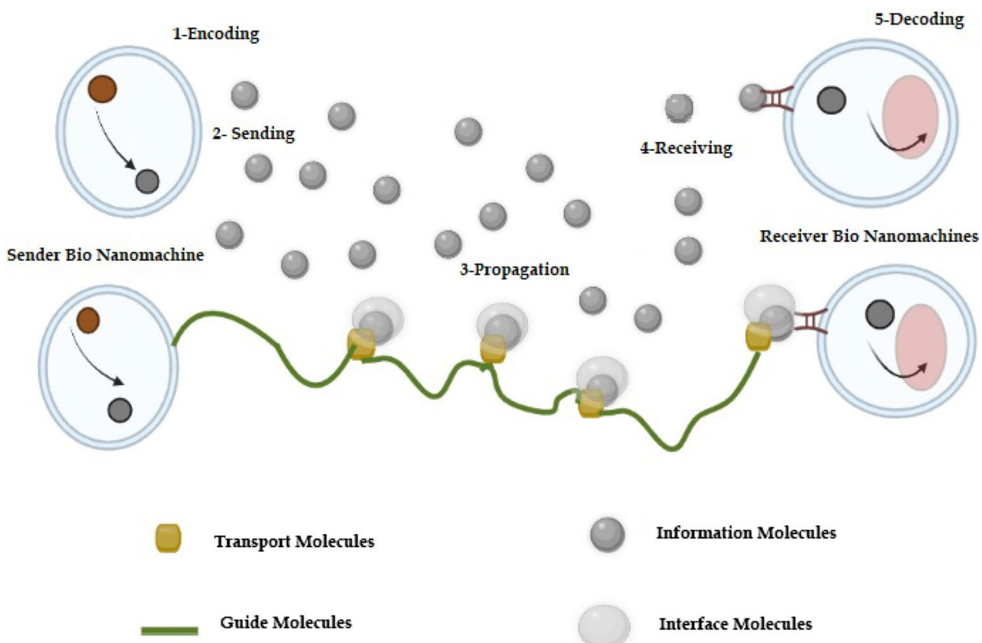

Fig. 1 Architecture of molecular communication (created with BioRender.com)

of implementing MC techniques in crops biotechnology has been developed by proposing a merger of MC and Crop biotechnology as a research area; we conclude the paper in the last section.

Structure of MC

MC is an evolving interdisciplinary study dedicated to sculpting, characterization, and engineering of communication systems where molecules and chemical reactions are responsible for information propagation. Due to its novelty, different simulation and experiment testbeds have been defined to explain its mechanism. Diverse types of MC approaches have been found in literature, where different characteristics have been considered for their categorization. In this review, we categorize the MC on the propagation of information molecules. Few basic propagation methods have been summarized here.

Natural propagation/diffusion

The unpredicted motion of a particle and its collision with other particles in its purlieu refer to a Brownian motion and can also be called diffusion. During this unpredicted motion, the particles that carry information can spread from the transmitting source to the receiving source by consuming already presented thermal energy in the channel environment. This shows that no external source of energy for propagation is essential in this type of molecular communication (Kadloor et al. 2012; Noel 2015; Farsad et al. 2016). This type of MC can be considered the most general and common MC option in nature, where examples are found in calcium signaling (Ca^{2+}) among cells (Nakano et al. 2005).

In a fluidic medium, like liquid or gas, the molecules can collide with the surrounding molecules or experience thermal vibration that may affect them (Jamali et al. 2019). Subsequent propagation of the molecules is entirely unpredicted and called Brownian motion. In 3-D Cartesian coordinates at a time *t*, let d*i*(*t*) = [x, y, z] denoted a vector to stipulate the place of the *i*th molecule. The unpredicted propagation can be modeled by this means (Berg 1993).

$$\mathrm{d}i(t+\Delta t) = \mathrm{d}i(t) + N(0, 2D\Delta t\mathrm{I}), \tag{1}$$

where Δt is the size of the time step and D in [m^2/s] is the coefficient of diffusion of the *i*th molecule. Further, $N(\mu, \Sigma)$ indicates a multivariate Gaussian random variable (RV) with mean vector μ and covariance matrix Σ, 0 is a vector with all zeros components, and the identity matrix is I. The diffusion coefficient regulates the propagation speed of molecules. Higher values of diffusion coefficient are directly proportional to the average transposition of the molecules in a specified timestamp. The coefficient of diffusion value is not only affected by the environment, but the size and shape of the particle may also affect its value. Einstein's relation can become the base for the determination of the coefficient of diffusion for orbicular particles plunged in a fluidic field, given as (Cussler and Cussler 2009).

$$D = k\mathrm{B}T/6\pi\eta R, \tag{2}$$

where kB gives Boltzmann's constant $value = 1.38 \times 10^{-23}$ JK^{-1}, T stands for temperature in kelvin, η is the (dynamic) viscosity of the fluid ($\eta = 10^{-3}$ kg m^{-1} s^{-1} for water at 20 °C), and the radius of the particle is denoted by R. It is notable that large particles have small values of the diffusion coefficient. Therefore, the effect of diffusion is limited to them.

Self-propagation or active transport

In an active transport, molecular propagation is carried out by following the pre-defined pathways connecting the transmitter with the receiver. The most widespread example from the literature of this type of MC is given by the use of molecular motors (Moore et al. 2006, 2009). Chemical energy is converted to kinetic energy by these molecular motors (Bustamante et al. 2001) that are protein filaments. Further, these filaments are the basis of force generation in biology, such as the muscles. Molecular motor filaments are studied in Moore et al. (2009) and Moore et al. (2006) and used to interconnect nanomachines physically and to produce the force for the information molecules from the transmitter to reach the receiver. The use of molecular motors and cytoskeletal filaments in active transport has been presented in Hiyama and Moritani (2010), and channel modeling for kinesin molecular motors moving over restrained microtubule is presented in Moore et al. (2009) and Enomoto et al. (2011). Simulations were used to associate the diffusion channels' arriving probabilities and channels of active transport using a track made of a protein named microtubule that links the transmitter to the receiver. Kinesin motor proteins are used over microtubule tracks to carry the information particles in this arrangement.

Propagation under external force

Gap junction (GJ)

GJ is another transmission mechanism of MC used in many applications. Intercellular connections adjacent to cells situated at the cell membrane are called gap junctions. Connexins serve as the pore that connects the cytoplasm of two neighboring cells. This channel allows for bidirectional ion and signaling molecule flow. This intrinsic signaling method was primarily studied for precise molecular communication by Nakano et al. (2007), where the two nanomachines transport the data via densely populated cells that are connected with each other through connexins. In Heren et al. (2013), the channel capacity was studied for the calcium signaling mechanism established on an intercellular calcium wave model for astrocytes. Oscillations of Ca^{+2} ion concentrations form calcium waves by the cytosol that propagate through adjacent cells using secondary messenger molecules. Different noise levels and symbol durations were adopted to analyze the channel capacity for the considered system. GJ-based MC system is also considered for binary-CSK modulation scheme presented in Nakano and Liu (2010). Simulation has been presented for the channel and possible information rates.

Catalytic nano-motors

Catalytic nano-motors typically comprise Au (gold) or Pt (platinum) nanorod particles that catalyze the available environmental chemical energy to impel themselves and carry small information-containing substances (Ye et al. 2021). Nanorods move in random directions without a governing magnetic field. However, nanorods can be directed to move in a particular route when guided by a magnetic field. The atmospheric conditions and their dimensions regulate the speed of these particles (Kaang et al. 2020). Characterization of physical channels and parameters are presented in Gregori et al. (2010), whereas direction controlling methodology for catalytic nano-motor is presented in Kline et al. (2005).

Bacterial-based communication

Bacterial-based communication under chemotactic response is predicted to have a comprehensive range of applications. In the *bacterial-based* type of communication, initially, a bacterium that gives response to some particular kind of attractants is selected and used as a communication vessel. Bacteria carrying DNA-based message in their cytoplasm are released into the environment. The bacteria drive themselves toward the receiving side using flagella, resulting in the release of attractant molecules by the receiver (Gregori and Akyildiz 2010). This shows that bacteria-based communication can be employed in different applications by analyzing its range to communicate, the capacity of the channel, throughput, and end-to-end delay, as studied in Cobo and Akyildiz (2010). Characterization of the physical channel and a simulation tool is presented in Gregori et al. (2011). Particles of attractant diffuse in the environment, and the property of bacteria to sense and move toward higher concentration of attractant is used as a primary tool for communication as shown in Fig. 2a, b.

BNSim, named simulation tool for bacterial-based communication, was introduced in Wei et al. (2013). Where the synthesis, emission, selection, and conversion of information-carrying molecules to cellular responses are studied with respect to biochemical processes due to their inherent viability for biocompatible environments as shown in Fig. 3,

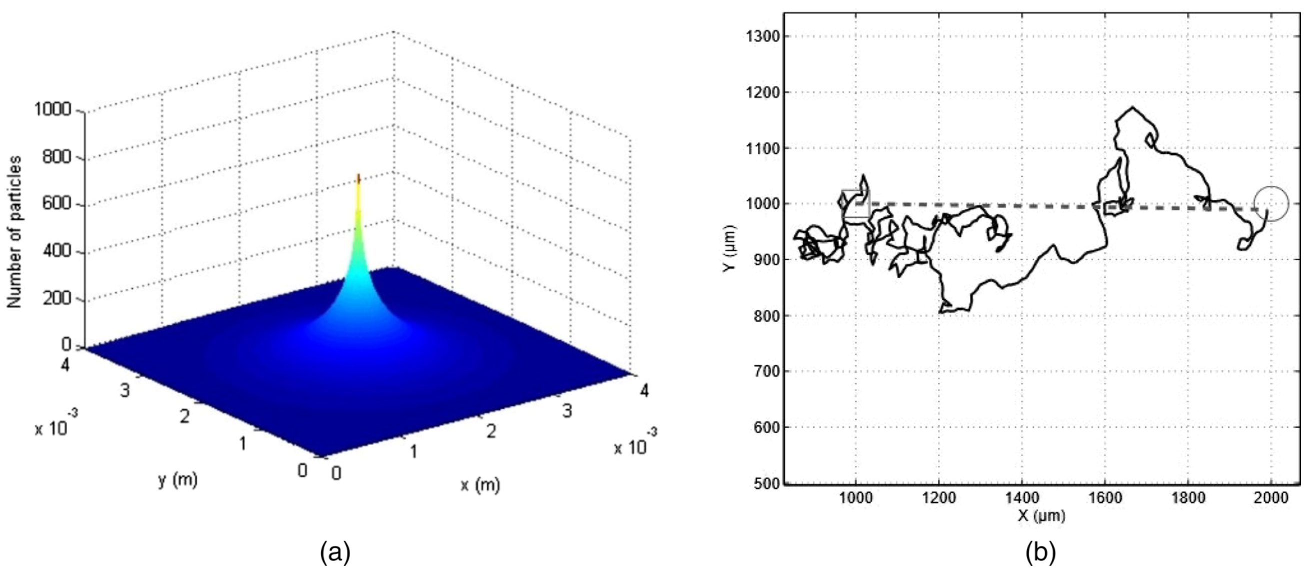

Fig. 2 Bacterial movement according to diffusion of attractant particles. **a** Diffusion of attractant particles. **b** Trace of a bacterium from Tx to Rx (Gregori et al. 2011)

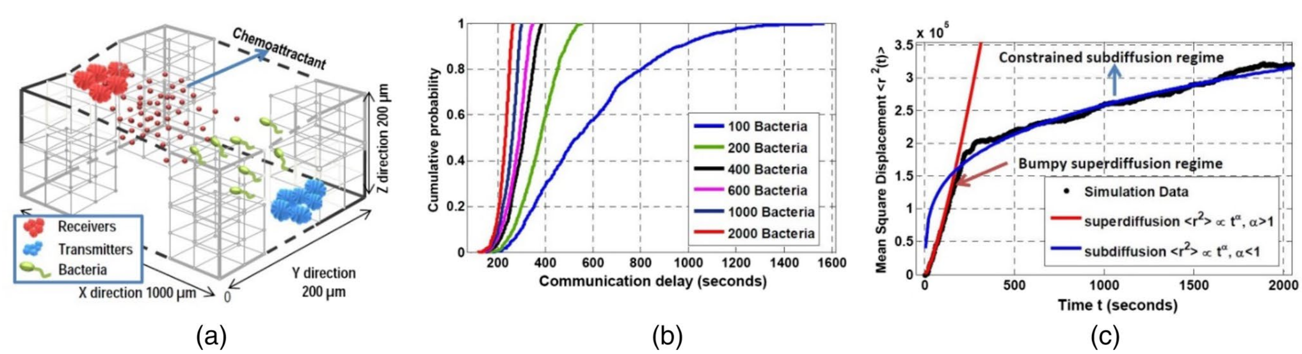

Fig. 3 Simulation results for **a** bacterial movement in 3D lattice space with solid boundaries toward attractant particle concentration. **b** Probabilistic values of communication delay are required for the delivery of message using cumulative distribution function. **c** Bacterial population diffusion along with mean square displacement with respect to time (Wei et al. 2013)

taking bacterium *Escherichia coli* as an exemplarily biological nanomachine.

Comparison of signal transduction in molecular communication network and plants

Signal transduction in plants

Considering the role of the phytohormones, ABA is one of them. Iit not only helps with the development and growth of plants, but is also involved in the integration of different signaling during stress and controls the responses of stress downstream. A model for initial abscisic acid transduction (Fig. 4) has been taken from Hubbard et al. (2010).

As illustrated in Fig. 4, during signal transduction of ABA, the initial actions of the signaling pathway follow the centralized signaling unit comprising the following proteins: (a) protein phosphatase 2Cs (PP2Cs), (b) SNF1-related protein kinase 2 s (SnRK2s) and (c) PYR/RCARs [PYRABACTIN (4-bromo-*N*-½pyridin-2-yl methyl_naphthalene-1-sulfonamide) RESISTANCE (PYR)/REGULATORY COMPONENT OF ABA RECEPTOR (RCAR) proteins. It is shown in this model that the PYR/RCARs is a receptor of abscisic acid; negative regulators of the pathway are PP2Cs, and downstream signaling is positively regulated by SnRK2s (Ma et al. 2009; Park et al. 2009). ABA-bound PYR/RCARs inhibit PP2C activity, and PP2Cs inactivate SnRK2s (Park et al. 2009; Umezawa et al. 2009; Vlad et al. 2009), establishing a double-negative regulatory pathway. Thus, PP2Cs become active and suppress the activity of SnRK2 and signaling toward downstream in the absence of ABA, whereas PYR/PYL/RCARs bind with PP2Cs and inhibit phosphatase activity in the presence of ABA, allowing SnRK2 activation and phosphorylation that subsequently regulate gene expression that pertains to ABA response. A comparison of plants' information systems and the MC system is presented in Table2.

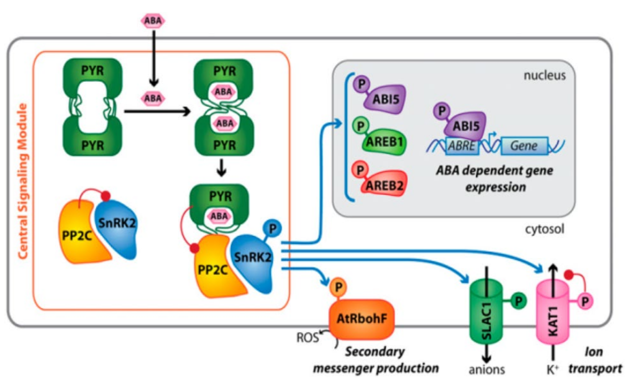

Fig. 4 ABA signaling (Hubbard et al. 2010)

Signal transduction techniques adapted in MC

In MC, data are coded into molecules *(information molecules or signaling molecules)* and transmitted to the receiver through an aqueous or gaseous medium. The average size of these information molecules, often called signaling molecules, is from a few nanometers to a few micrometers. Protein molecules, DNA and RNA (nucleic acid) molecules, elemental ions, neuronal signaling (neurotransmitters), lipid membranes, and vesicles are the most critical information molecules. The most significant characteristic of any data molecule is chemically stable. We will provide an overview of these chemically stable knowledge molecules in the following few paragraphs.

(a) Protein molecules: (Nakano et al. 2013); Proteins are one of the essential building blocks of biological systems manufactured by nature. Chemical reactions are catalyzed by proteins, and certain proteins are called enzymes. An enzyme has a catalytic domain in which it transforms substrates into products. (a) An enzyme E binds to a specific substrate S in its simplest form (Fig. 5) to form an enzyme–substrate complex ES; (b) ES then either dissociates back into E and S or (c) transforms into E and product(s) P. Note that the reaction does not change the enzyme itself.

Table 2 Comparison of plants' communication system and molecular communication system

Comparison of plant's molecular communication system and molecular communication system		
Communication features	Plant's molecular communication method	Molecular communication method
Information type	Molecules	Molecules
Transmission of data	The chemical process under different stresses	Chemical states and process
Propagation	Diffusion under external environmental conditions	Physical transportation or diffusion
Reception	Chemical process	Chemically driven process
Medium	Aqueous or gaseous	Aqueous or GASEOUS
References	(Ballaré and Casal 2000; Yoneya and Takabayashi 2014; Karban et al. 2006; Braam 2005)	(Akyildiz et al. 2008; Suda and Nakano 2018; Moore et al. 2006)

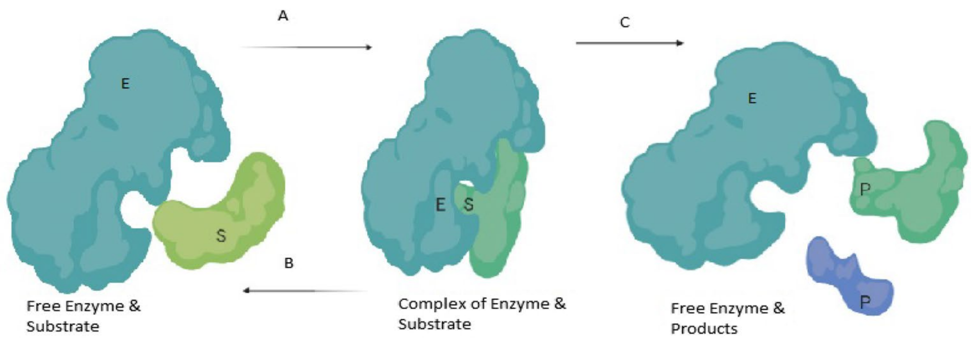

Fig. 5 Conversation of the substrate into products under enzymatic reaction (created with BioRender.com)

Enzymes are involved in many chemical reactions in biological systems that occur very slowly or are not likely to occur without an enzyme.

Transducing signals are another significant feature of proteins within biological cells. Signaling molecules, referred to as ligands (e.g., hormones, growth factors), bind to particular receptors that identify and cause chemical reactions in the form of a signaling molecule with high specificity. Ligands as well as receptors, proteins or peptides often act to form ligand–receptor structures that are commonly found in biological cells. A cell surface receptor that has three spatially distinct domains is one common and essential type of protein receptor: extracellular, transmembrane, and intracellular (Fig. 6).

From the cell membrane, the extracellular domain projects and is exposed to the extracellular space. Usually, the extracellular domain has binding sites in the extracellular space to identify ligands. In the cell membrane, the transmembrane domain is stable and provides a mechanism for transmitting signals from the extracellular domain to the intracellular domain. One channel type is an ion channel that opens when a ligand binds to its extracellular domain and allows ions in the intracellular and extracellular space to diffuse across the cell membrane.

Another primary function of proteins in biological cells is to generate motion. *Motor proteins*, also called *molecular motors*, such as myosin, kinesin, and dynein, are specialized in generating motion. Motor proteins are mechanochemical enzymes that convert chemical energy into a mechanical force. A motor protein consists of functional domains, including the head, neck, and tail domains (Fig. 7). The motor protein absorbs the energy to change its conformation and moves along the rail. In one model, one head is attached to the rail, while the other head, which is detached from the rail, takes one step forward and then attaches to the rail. The first head is then detached to make another step. A repeating cycle of such motion leads to the directional movement of the motor protein from one end of the molecular rail made of protein polymers to the other end and transports molecules to specific locations within cells.

(b) DNA and RNA molecules: Nucleic acids, i.e., ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), are also the most biocompatible and chemically stable information molecules. The carrying of information from one generation to another is DNA's responsibility. As messenger molecules, RNA is utilized for intercellular communication in plants and animals by catalyzing biological reactions, such as confined neuronal growth and protein synthesis (Donnelly et al. 2010; Mittelbrunn and Sánchez-Madrid 2012). Similarly, nucleic acids can take apart in the molecular-based transmitter to transport data. Due to current progress in sequencing techniques and synthesis of DNA/RNA, it is possible to have molecular communication that can use encoded DNA (Slonkina and Kolomeisky 2003; Bell and Keyser 2016).

(c) Elemental or essential ions: Numerous operations in natural systems are dictated by essential ion mediators such as Na +,

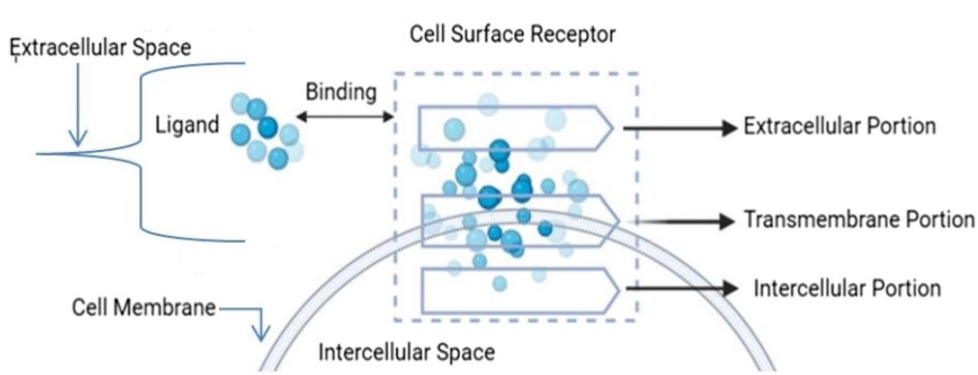

Fig. 6 Signal transduction via cell surface receptors (created with BioRender.com)

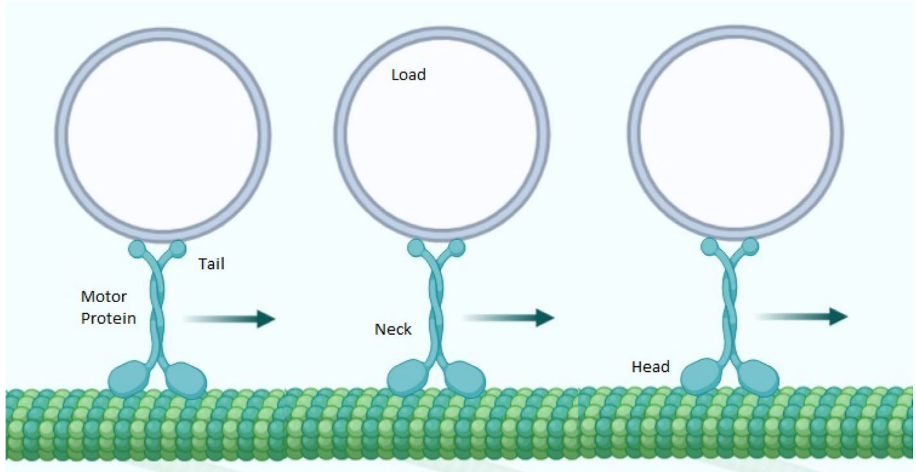

Fig. 7 Motor protein over the molecular rail (created with BioRender.com)

K +, and Ca2 +. In plants, Ca2 + ions are used as a second messenger to complete signaling mechanisms in signal transduction pathways (Tuteja et al. 2007). In the case of MC, different types of stimuli cause the absorption or release of Ca2 + ions from sensory neurons or cardiomyocytes that open/close particular channels on the cell membrane. This kind of variation in the concentration of Ca2 + ions can be modulated in the form of frequency and modulation to encode the information (Denizot et al. 2019). This indicates that essential ions can also be used as a solution to communicate with living organisms for a conceivable solution like monitoring.

(d) Lipid membranes and vesicles: Vesicles can resemble small vessels of molecules encapsulated within spherical lipid membranes. The membrane of a vesicle comprises two layers of phospholipid molecules, known as lipid bilayers (Fig. 8). Each phospholipid molecule in a lipid bilayer has one hydrophilic head and two hydrophobic tails (Nakano et al. 2013).

(e) Neural signaling (neurotransmitters): Neurons use a chemical and electrical signal to communicate with each other called neuron spike communication (Balevi and Akan 2013). The interface of neurons is currently under consideration for new solutions, e.g., treatment of injured spinal cord, neural prosthetics, and brain–machine interaction. By utilizing the particular method of neural communication, a simulation technique WAS developed, i.e., neural transmitters that can provide maximum output. Different manners are used as a transmitter for the furthermost neurotransmitters, which are studied thoroughly in Uguz et al. (2017) and Jonsson et al. (2016).

Relationship between molecular communication and plants' molecular communication

Intercellular plant hormone molecular communication is mediated by extracellular plant hormones' molecular signals, such as proteins, peptides, amino acids, and steroids. Most cells in plants can transmit and receive bioengineered plant

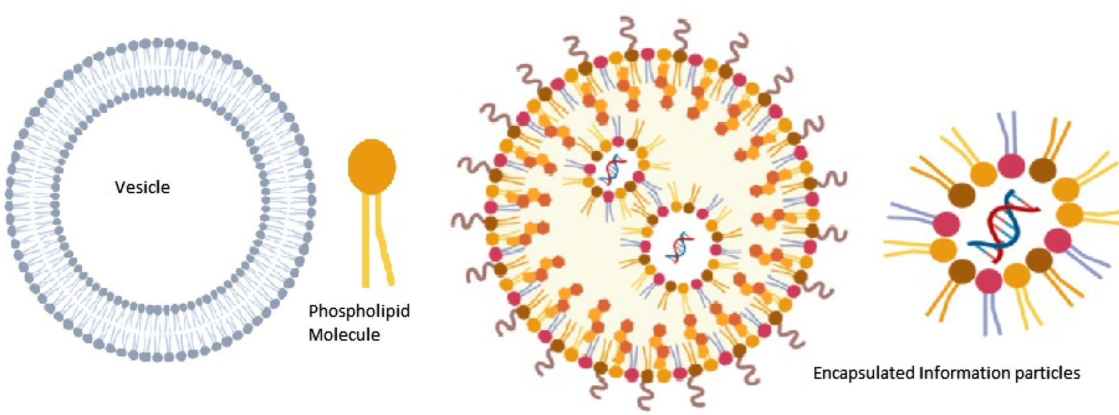

Fig. 8 Encapsulation of Information particles within vesicle (created with BioRender.com)

hormone molecular signals. For the emission of plant hormone molecules, bioengineered plant hormone molecules can either diffuse inside the cell membrane of a plant or be transmitted between cells. Whereas, in MC, the synthetization, emission, collection, and conversion of information-carrying molecules to cellular responses through biochemical processes can be studied because of their inherent capability for biocompatible atmospheres. The challenge involved is to recognize in a way that these natural solutions can be controlled, modified, or re-engineered for the transmission of information that can be dissimilar from the natural. MC systems can actualize the engineering component of genetically altering cells' activities inside their natural communications, using the technologies outlined above that are being developed in synthetic biology and nanotechnology (Pierobon 2014).

Research on MC has described the methods for assembling the biological and chemical components that can be utilized as practical systems to perform MC. There are many interdisciplinary applications of MC that can be found in biological engineering, medical and healthcare, industrial, environmental, and information and communication technology areas (Akyildiz et al. 2008; Moore et al. 2007; Nakano et al. 2012). The aforesaid discussion depicts that MC is closer to plant signaling, and it can be used as a helpful tool in crop biotechnology to form Plants' molecular communication. We suggest that the MC technique may be used to explore further the plant transduction from stimuli, receptors, and second messenger to cellular response. These MC systems have already existed in nature and took a long time that spans over billions of years to develop into their present shape. These structures can be seen all around us and even within our bodies (Gilroy and Trewavas 2001).

The proposed structure for bacterial-based plants' molecular communication network

"The development of tolerant plant species would be more likely if it is possible to understand and control the activities of plant hormones under stress." Keeping this in view, we suggest a basic structure of the bacterial-based plant's molecular communication. Brushing up with plants' communication found in literature, plants not only respond at the molecular level to single abiotic stress, but also to biotic interactions. A complex network of signaling pathways modulated these responses initiated by a variety of small molecules (Nguyen et al. 2016). This complicated signaling pathways network that is initiated by various tiny molecules is responsible for modulating these responses, including signaling of Ca^{2+} (Seybold et al. 2014), reactive oxygen and nitrogen species (Wang et al. 2013; Baxter et al. 2014), and phytohormones-like auxin, cytokinin, gibberellin, ethylene and abscisic acid (Peleg and Blumwald 2011; Pieterse et al. 2012; Kazan 2015).

Inter/intraplants' communication is based on the exchange of information molecules to communicate, which has also been considered a mode of communication in MC. This forms our inspiration for the bacterial-based plant's molecular communication, and it has two fundamental things, i.e., (i) bacterial properties and (ii) plant's molecular communication. In the first part, we discuss the innate ability of bacteria as an information carrier, whereas in the second part we discuss the internalization of bacteria in plants and how it can be advantageous for us.

Bacterial properties

Bacteria as information carrier

In general, a bacterium has the property to assess its intracellular and extracellular environment and can promptly react to any change by sensing mixtures of molecules (Camilli and Bassler 2006). Bacteria, e.g., *Escherichia Coli (E.Coli)* (Fig. 9), can swim in a liquid medium by using flagella and have the property of chemotaxis to assess the concentration gradient via chemoreceptors and swim toward higher attractant concentrations. Furthermore, the exemplary bacterium *E. Coli* has the properties of sensing specific attractants (Goldberg et al. 2009). Due to the information-carrying property of bacteria, it can carry information that is encoded in its DNA from a transmitter and deliver it to the receiver (Gregori and Akyildiz 2010).

Genetically modified bacteria

We believe that it is possible to have genetically engineered bacteria and utilize existing biological parts for detection, understanding, and even modification of plant's molecular communication. These components may also be mixed and matched to achieve particular behaviors. A biological component is a collection of genes that allow bacteria to perform specific functions such as chemotaxis or reproduction. There are numerous examples of teams that have completed the job, and a publicly accessible registry of standard biological parts with thousands of parts is available (Cobo and Akyildiz 2010), whereas the use of genetically modified bacteria for delivery of drug in the human body is explained in Wegmann et al. (2017).

Model bacterium *Escherichia Coli (E. Coli)*

Due to the detailed knowledge of its nucleic acid and protein biosynthetic pathways, *E. coli* is a preferred host for the study of phage biology. It is a preferred host for gene

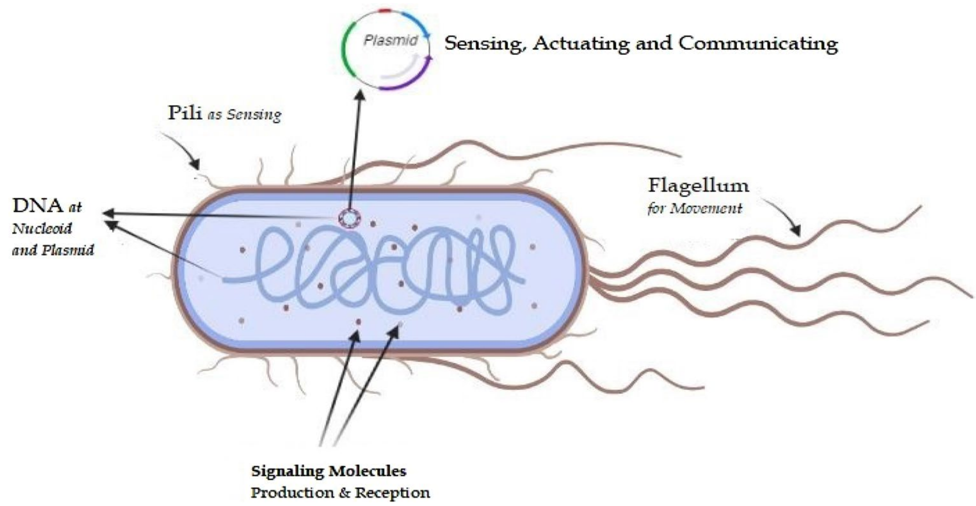

Fig. 9 *E. Coli*, created with BioRender.com

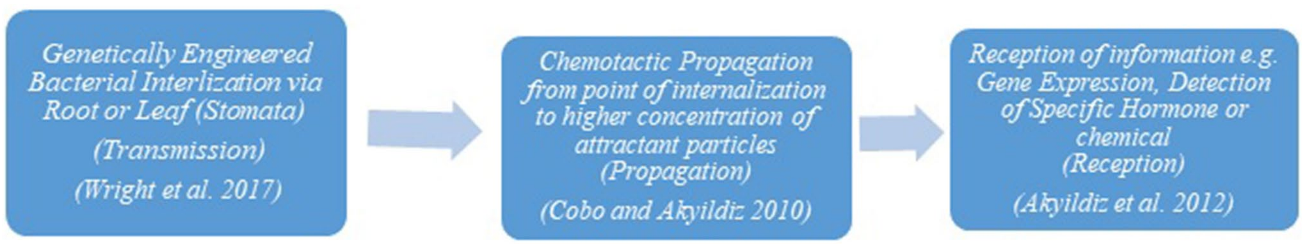

Fig. 10 Architecture of research

cloning due to the high efficiency of introducing DNA molecules into cells and for protein production due to its rapid growth and ability to express proteins at very high levels. *E. coli*'s ability to grow under chemically defined conditions, combined with its broad genetic toolbox and the trait of bacterial conjugation, which allows large DNA segments to be transferred from one bacterium to another, makes it a crucial system in the study of bacterial metabolic pathways (Cronan 2014). A genetically modified *E. Coli* can act as a messenger, carrying messages encoded in its DNA from the transmitting side to the receiving end and biomolecular sensing and bioluminescence (Akyildiz et al. 2012).

The use of bacteria for the contact between eukaryotic cell-sized nanodevices is an example of this mechanism. The contact is accomplished by exchanging DNA molecules, which are carried by bacteria using chemotaxis to transport them (Cobo and Akyildiz 2010; Tsave et al. 2019).

Plant's molecular communication

As discussed earlier, plant not only responds to abiotic stresses, but also to biotic interactions at the molecular level, forming a complex network of signaling pathways. Studies revealed that bacteria like *Escherichia coli* internalize into plant roots and reach the shoot (Wright et al. 2017; Sharma et al. 2009), and with the help of these properties of plants and bacteria, we can formulate some new research directions for crops. The fact that bacteria can internalize into plants, as well as the bacterial properties that have been used to establish Molecular Communication Networks and Plant Molecular Communication, can articulate a research direction that will use genetically modified bacteria as sensors, hormone or disease detectors, targeted gene expression, and a bioluminescence feedback communication system. Further, plants can be utilized as readymade infrastructure for molecular communication. The proposed research architecture is shown in the following flow chart (Fig. 10).

Conclusion

MC has achieved a milestone in Biomedical applications (like Targeted Drug Delivery, Health Monitoring using Biosensors), Environmental Applications (Like Monitoring of Environment, Controlling of Waste and Pollution), Industrial Applications (Like Production of Biofilms); crop biotechnology is also one of the fields that can be served by adopting MC's novel techniques. A new era of biosensors can be opened by taking advantages of the conceptual models of MC. Research can be carried out with the help of genetically engineered bacteria to study plant hormones and processes at even the nanoscale. Nevertheless, plant signaling can be mediated with the help of MC, which is an open area of research. The main idea of this review is to present the potential of MC that would be used as a way forward for advancement and new study in the field of crop biotechnology. We hope that this work will open new doors of collaborative research of different disciplines to expand the experiments in crop biotechnology and for the betterment of humanity.

Author contribution statement SA: prepared and presented the work, wrote the original draft. JH: supervised and conceptualized the work. SMZAN: reviewed and edited the work. YZ: provided the study materials and maintained the research data. LL: project administration. AMI: management activities to annotate and reproducibility of research outputs.

Acknowledgements No funds, grants, or other support was received.

Funding No funds, grants, or other support were received.

Data availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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