



A brief review on the development of glowing plants through various bioluminescence system

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Abstract

Bioluminescence is a common natural phenomenon in which light is generated and emitted by living organisms in the presence of oxygen. Bioluminescence plants represent a novel frontier in sustainable biotechnology, bringing together natural illumination and synthetic biology. There have been transformed with bioluminescence gene to originate in living organism or plants so far – from bacteria, fungi, insects (e.g. fireflies), worms, marine organism, algae, dinoflagellate, jellyfish, earthworm, and sea star fish – have been successfully introduced into plant genomes. As a result, researchers are now developing self-sustaining, light-emitting plants that do not require external electricity. In recent years, several bioluminescence systems have been identified and applied in plant research. These include the luciferase-luciferin system, PBIN technique, bacterial bioluminescence system, caffeic acid cycle (CAC), and fluorescent proteins (FPs). These systems have enabled the development of glowing plants that are clearly visible to the naked eye, even in dark environments. This review summarizes the existing current literature on the reconstruction and integration of bioluminescent systems for the development of autoluminescence in plant cells. Looking toward the future possibilities, bioluminescent plants could be used not only in scientific research but also as an alternative, eco-friendly source of artificial lighting. As future societies seek innovative solutions to climate and energy challenges, bioluminescent plants represent a promising and symbolic step toward a more regenerative and ecologically integrated future.

Keywords: Bioluminescent system, Genetic engineering, Sustainable development

Introduction

Bioluminescence reaction is a natural form of light production exhibited by living organism, observed in more than 10,000 species across more than 800 genera (Haddock *et al.*, 2010) [17]. It involves a specialized biochemical reaction that enables these organisms to emit visible light. Bioluminescence functions as a unique form of chemical signalling often associated with communication, camouflage, or predation. The term bioluminescence generally refers specifically to a biochemical process in which a light – emitting compound, known as luciferin, is biosynthesized within the luminous organism and oxidized by the catalytic action of a luciferase enzyme in the presence of oxygen. This reaction releases energy in the form of visible light (Shimomura 2006) [41]. The phenomenon is a striking example of how biological systems can produce light through enzymatic activity. Bioluminescence occurs through a biochemical reaction involving different types of proteins called luciferases, which catalyse the oxidation of substrates known as luciferins. Among recent studies, a particularly relevant review highlights the contributions of scientists working on the development of glowing plants (Li *et al.*, 2021). Recently; several new genera of bioluminescent species were discovered in the forest of Meghalaya, India (Karunaratna *et al.*, 2020) [22]. Bioluminescence is often exhibited through the photoluminescent activity, which allows organisms to glow continuously for a short or long extended period in the absence of external light. Alternative strategies for developing novel bioluminescence systems are currently emerging. Many fungal species naturally produce light-a phenomenon referred to as bioluminescence or sometimes fluorescence, depending on the underlying

mechanism. During the past years, fluorescent genes and bioluminescence systems have been identified in proteins that are believed to influence the expression of native luminescence genes (Kim and Paulmurugan 2021) [25]. The presence of bioluminescent systems provides certain living organisms with physical advantages in specific ecological contexts, such as communication, mating, or predation avoidance. A well-known example is the bioluminescence jellyfish *Aequorea Victoria*, which expresses green fluorescent protein (GFP) along with the photoprotein aequorin (Morise *et al.*, 1974). Bioluminescent genes have been synthesized or isolated from various organisms, including fungi, bacteria, insects (e.g. fireflies), marine organisms, algae, dinoflagellate, jellyfish, worms, and sea star fish (John 2008) [21].

In most cases, light emission in bioluminescence results from chemical oxidation. Bioluminescent genes produce cold light (light without significant heat) in the presence of oxygen; however, this phenomenon does not naturally occur in higher plants on Earth. Recently, a few plants have been genetically modified using bioluminescence system – such as the caffeic acid cycle, bacterial bioluminescence operons, and the luciferase-luciferin system – allowing them to emit light in darkness, clearly visible to naked eye. These modifications provide a distinct lighting advantage and demonstrate the potential for bioluminescent plants through modern biotechnological techniques (Mitiouchkina *et al.*, 2020) [32]. By introducing luminescent systems into plant cells, it is now possible to use these traits as biomarkers or for sustainable lighting applications. Several plant species have been successfully transformed with bioluminescent systems, including – Arugula (*Eruca sativa*), Kale (*Brassica oleracea*), Spinach (*Spinacia oleracea*), Watercress

(*Nasturtium officinale*), and Tobacco (*Nicotiana tabacum*) plants using the bioluminescent system to produce glowing light (Kwak *et al.*, 2017 and Mitiochukina *et al.*, 2020) [30, 32]. Furthermore, engineered bioluminescent plants have been developed using ATP-powered, genetically encoded, high-autoluminescent systems as sustainable alternatives to conventional lighting sources (Gordiichuk *et al.*, 2021) [21]. Bioluminescent plants may be useful not only for basic plant research but also for ornamental purposes, providing a novel aesthetic property through glowing flowers and plant tissues. Researchers have successfully developed plants with self-sustained bioluminescence genes. These autoluminescent plants are engineered to express fungal or bacterial bioluminescence systems that converts caffeic acid into luciferin, enabling them to produce continuous, visible light without external inputs.

Bioluminescence results from a biochemical reaction involving a luciferase enzyme and a luciferin substrate, typically requiring molecular oxygen and sometimes cofactors such as ATP and NADH. The light-emitting reaction is catalysed by luciferase, a key enzyme in this process (Fleiss and Sakisyan 2019) [13]. Bioluminescent plants, developed through the integration of gene pathways from fungi, bacteria or marine organisms, represent a novel and promising approach to advancing sustainable development in modern society. These genetically engineered organisms can autonomously emit visible light without relying on external energy sources, making them a potential alternative to conventional lighting systems. Their applications go beyond ornamental use, offering benefits such as reduced electricity consumption, lower carbon emissions, and the potential to support innovative green infrastructure in urban planning. Additionally, bioluminescent plants could serve as biosensors for environmental monitoring and contributing to ecological awareness and effective management. Recent advancements in synthetic biology including successful expression of fungal bioluminescence genes in plants (Mitiochukina *et al.*, 2020) [32], underscore the feasibility and future potential of this technology.

Mechanism of Bioluminescence: Bioluminescence typically involves the oxidation of a substrate (luciferin), catalysed by an enzyme (luciferase), resulting in the emission of light. In some marine species, luciferase and luciferin are components of a single complex known as a photoprotein, which requires additional cofactors to function properly. The colour of the emitted light depends on the specific luciferin-luciferase system and can range from blue to red (Duchatelet and Dupont 2024) [8].

The basic principles behind light emission are as follows -

1. Reaction: A chemical reaction produces bioluminescent activity, which is a type of autoluminescence in which light is emitted. The reaction rate of luciferin oxidation is controlled by the enzyme luciferase, which catalyzes the conversion of luciferin into oxyluciferin, generating visible light. Luciferin is the primary substrate in the bioluminescence reaction and its oxidation (oxyluciferin) along with the involvement ATP and NADH is facilitated by the specific enzyme luciferase.



2. Reaction: In the bioluminescent chemical reaction of fireflies, the key components are the enzymes luciferin and luciferase. In this process, luciferin is converted into luciferyl-adenylate by ATP in the presence of magnesium ions (Mg^{2+}). Mg^{2+} and ATP are essential for the reaction, while adenosine monophosphate (AMP) and pyrophosphate (PP) are released as byproducts.



3. Reaction : Bioluminescence results from oxygenation reactions, where molecular oxygen reacts with luciferin, producing energy in the form of light. In this process, luciferase-D-luciferyl-adenylate is oxidised by oxygen to form luciferase-oxyluciferin, releasing photons of visible light. During the reaction luciferase facilitates the oxygenation of luciferin, ultimately forming oxyluciferin and emitting light.



4. Reaction: At the core of all bioluminescent systems lies a reaction between luciferin (the substrate) and luciferase (the enzyme). This reaction typically involve the oxidation of luciferin, emission of a photon (visible light), and in some systems such as the firefly, regeneration of the substrate as part of the bioluminescent operating cycle.



5. Reaction : In some organisms, additional cofactors are required for the reaction to occur. For example, in bacterial bioluminescence, reduced flavin mononuclear (FMNH_2) acts as a cofactor. *Aliivibrio fischeri*, a marine bacterium, produces light through a luciferase-catalyzed reaction involving FMNH_2 , oxygen, and a long chain aldehyde. This bacterium often forms a symbiotic relationship with marine animals, such as the Hawaiian bobtail squid, providing camouflage through a mechanism known as counter-illumination.



- **Luciferin:** The light-emitting substrate
- **Luciferase:** The enzyme that catalyzes the reaction
- **ATP:** Provides energy and activates luciferin
- **Mg^{2+} :** Essential cofactor for luciferase activity
- **O_2 :** Required for oxidation
- **RCHO:** Long-chain aliphatic aldehyde (tetradecanal)
- **RCOOH:** Long-chain fatty acid (tetradecanoic acid or myristic acid)
- **FMN:** Oxidized flavin
- **FMNH₂:** Reduced flavin mononucleotide

In the present review highlights recent progress in the development of bioluminescent of bioluminescent systems

in plants cells as well as the contributions of various scientist toward the successful creation of glowing plants

that produce emit light using different bioluminescence system.

Table 1: Contributions of Different Scientists to the Development of Glowing Plants

Luminescence gene source	Engineered plants	Derived from	Gene introduces	References
Firefly	Nicotiana tabacum	Photinus pyralis	Firefly luciferase	Ow <i>et al.</i> , (1986)
Firefly	Daucus carota	Photinus pyralis	Firefly luciferase	Ow <i>et al.</i> , (1986)
Bacterium	Nicotiana tabacum	Photobacterium leiognathid	luxCDABEG	Krichevsky <i>et al.</i> , (2010) [29]
Nano-lantern	Nicotinan benthamiana	Artificial nano-lantern	pH2GW7-CT nano-lantern	Saito <i>et al.</i> , (2012) [39]
Fluorescent protein	Torenia fournieri	Chiridius poppei	CpYGFP	Sasaki <i>et al.</i> , (2014) [40]
<i>N. tabacum</i>	Neonothopanus nambi	H3H, Hisps, Luz and CPH	Fungus luciferase	Mitiouchkina <i>et al.</i> , (2020) [32]
Firefly	Brassica oleracea	Photinus pyralis	Firefly luciferase	Kwak <i>et al.</i> , (2017) [30]
Firefly	Spinacia oleracea	Photinus pyralis	Firefly luciferase, luciferin and CoA	Kwak <i>et al.</i> , (2017) [30]
Fluorescent protein	Chrysanthemum morifolium	Chiridius poppei	CpYGFP	Kishi-Kaboshi <i>et al.</i> , (2017) [26]
Fluorescent protein	Petunia hybrida	Chiridius poppei	eYGPuv	Chin <i>et al.</i> , (2018) [4]
Fungi	Petunia hybrida	Aspergillus nidulans and Neonothopanus nambi	NPGA, H3H, Hisps, Luz, and CPH	Khakhar <i>et al.</i> , (2020) [24]
Fungi	Nicotiana benthamiana	Aspergillus nidulans and Neonothopanus nambi	NPGA, H3H, Hisps, Luz, and CPH	Khakhar <i>et al.</i> , (2020) [24]
Fungi	Catharathus roseus	Aspergillus nidulans and neonothopanus nambi	NPGA, H3H, Hisps, Luz, and CPH	Khakhar <i>et al.</i> , (2020) [24]
Rosa rubiginosa	Aspergillus nidulans and Neonothopanus nambi	NPGA, H3H, Hisps, Luz and CPH	Fungus luciferase	Khakhar <i>et al.</i> , (2020) [24]
Nano-lantern	Arabidopsis thaliana	Artificial nano-lantern	Green enhanced nano-lantern (GeNL)	Furunata <i>et al.</i> , (2020) [24]

Glowing plants with bioluminescent system

The bioluminescent system remains largely understudied, yet it is increasingly utilized in various research areas. Several techniques have been developed and employed to achieve this goal, including microinjection, the gene gun technique, liposome-mediated delivery, electroporation technique, PBIN, spray method, and *Agrobacterium tumefaciens* mediated transformation method.

Up to now, five natural bioluminescent systems, originating from fireflies, bacteria, fungi, and fluorescent proteins have been reconstructed in plants and used to produce light through chemical reactions. These reactions, which generate visible light, occur within living organisms. Plants are capable of producing specific chemical reactions that result in light emission. Scientists have now developed methods to artificially replicate this phenomenon, enabling plants to glow using introduced bioluminescent systems.

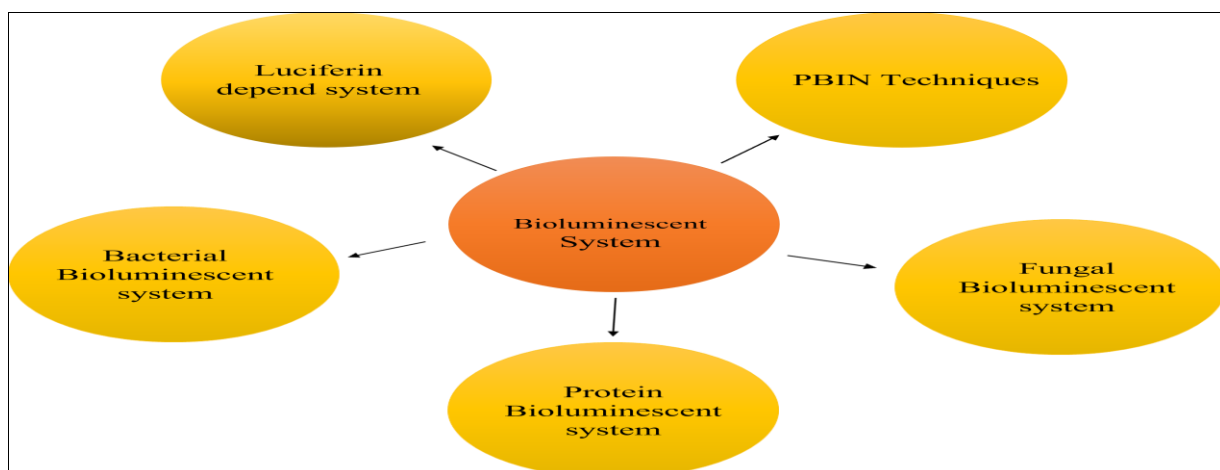


Fig 1: Five types of natural bioluminescent system

Natural bioluminescent system

1. D-Luciferase depend system

In fireflies, the bioluminescent system was first introduced into plants by incorporating the *Photinus pyralis* luciferase gene into *Daucus carota* and *Nicotina tabacum* – a system known as the firefly luciferase-luciferin system (Ow *et al.*, 1986). Different luciferin-luciferase systems – such those from bacteria, fungi, fireflies, and coelenterazine-based marine organisms – exhibit inherently distinct emission spectra. The D-luciferine-dependent luciferin system is considered one of the most practically significant and widely studied types of bioluminescence reactions. It has evolved independently in several lineages of beetles within the order Coleoptera families including fireflies (*Lampyridae*), click beetles species (*Elateridae*) and railroad worms (*Phengodidae*). These organisms produce glowing light with emitting wavelengths ranging from 540-640nm, covering a green to red fluorescent light. These chemical

reactions utilise a stable and non-toxic compound (Tiffen *et al.*, 2010, Viviani *et al.*, 2011, Kotlobay *et al.*, 2020) [27, 42, 44].

Firefly luciferase can be expressed either independently or fused with proteins of interest in various plant organs, such as roots, stems, and leaves, during advance transgenic plant development in the research area (Li *et al.*, 2021). This system provides a valuable tool for studying protein expression, localization and protein-protein interaction (PPIs). The firefly luciferin is catalyzed firefly luciferase gene in the presence of magnesium ions (Mg^{2+}), molecular oxygen (O_2), and ATP producing a yellow-green luminescence. Additionally, coenzyme A (CoA) can be used to reduce the oxidized light-emitting compounds found in living organisms, thereby sustaining that generate bioluminescence (Gosset *et al.*, 2020) [16].

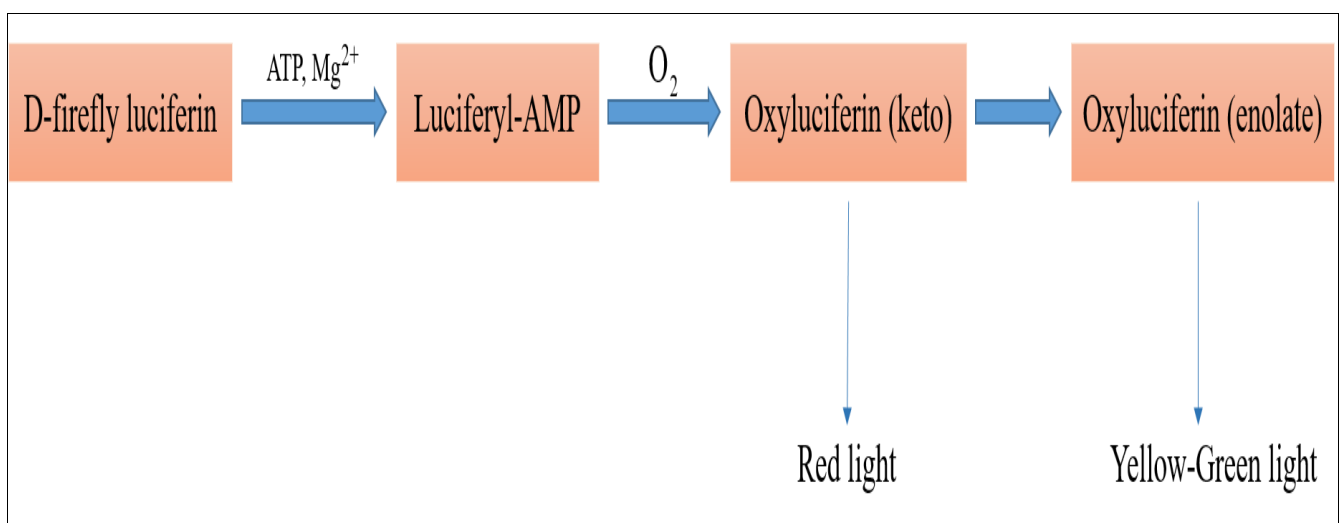


Fig 2: The firefly luciferase bioluminescent reaction

2. Glowing plant in Pressurized bath infusion of nanoparticles (PBIN)

In 2017, researchers developed a novel nanotechnology method known as Pressurized Bath Infusion of Nanoparticles (PBIN) was developed. The PBIN method works by applying external pressure to facilitate the infusion of nanoparticles into the internal microchannels of the leaf mesophyll cells. In this technique, firefly luciferin and Coenzyme A (CoA) are encapsulated into two separate nanocapsules, while luciferase is conjugated to the outer surface of silica-PEG nanocarriers. These nanoparticles help reduce luciferin toxicity and prevent the artificial denaturation of luciferase, resulting in a sustained light-emitting degeneration period of up to 8 hours in plant cells. In this work, to insert the nanoparticle mixture into the entire plant cells, an advance infusion method was developed using the stomatal pores on the leaf's surfaces. The objective was to engineer a nanobionic plant by integrating four distinct types of nanoparticles, each designed to carry specific proteins and components necessary for constructing a self-sustaining photonic system capable of generating both direct and indirect light sources. These chemically interactive nanoparticles were targeted toward the plant's mesophyll and guard cells, which are

typically rich in ATP levels. The preparation of the nanoparticle system for light production of the nanoparticle system for light production involved the following components: (1) SNP-Luc: an immobilized silica nanoparticle conjugated with luciferase immobilized using poly (ethylene glycol) bis (amine) (NH_2 -PGE, molecular weight; 2,000 Sigma), (2) PLGA-LH₂: D-luciferin encapsulated within poly (lactic-co-glycolic acid) (PLGA) nanoparticles, serving as the substrate for light emission, (3) CS-CoA: Chitosan nanoparticles (medium molecular weight; Sigma) loaded with Coenzyme-A (CoA) and crosslinked gradually with tripolyphosphate (TPP; Sigma). CoA facilitates sustained light emission by regenerating firefly luciferase through reaction with dehydroluciferyl-adenylate, and (4) SNP-AF: Silica nanoparticle tagged with Alexa Fluor 488-cadaverine and silane to track nanoparticle uptake and localization within plant tissues.

The nanoparticle mixture was introduced into the entire plant using the Pressurized Bath Infusion of Nanoparticles (PBIN) technique, in which the whole plant is briefly immersed in a pressurized aqueous chamber. PBIN was successfully performed at a saturation pressure of 1.8 bar and achieved successful nanoparticle delivery without inducing membrane damage (Kwak *et al.*, 2017) [30].

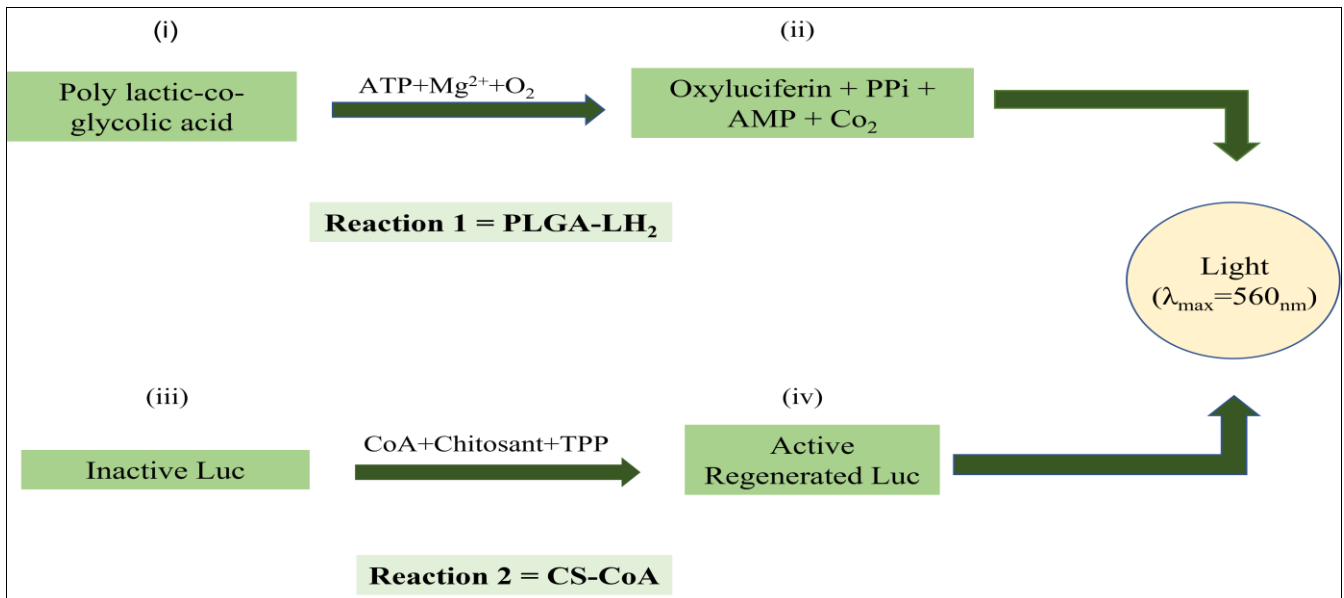


Fig 3: Reaction mechanism of light production by firefly luciferase using Nanoparticles

3. Bacterial bioluminescence system

The first successful integration of a bacterial bioluminescent system in plants was demonstrated in *Nicotiana tabacum*. Since then, only a limited number of bacterial luciferase-luciferin systems have been expressed in other transgenic plants species (Krichevsky *et al.*, 2010) [29]. All bioluminescent bacteria share a similar mechanism to creating luminating brighter light, in which photons are produced in a set of biochemical reactions utilizes flavin mononucleotide (FMN) and long-chain aldehyde derivative. These bioluminescent genes can be engineered into plastids to develop self-sustaining, light-emitting plants. The genetic components of this system originate from three genera of gram-negative, motile, rod-shaped luminescent bacteria that is *Photobacterium*, *Vibrio* and *Xenorhabdus* (Piyush *et al.*, 2022) [36]. The light-emission system in luminous bacteria, responsible for enzymatic catalyzing luciferin biosynthesis and bioluminescent system is encoded by the *lux* operon. The highly conserved *lux* operons (*luxCDABEG*) is found across various species of luminous bacteria and encodes the

complete bacterial bioluminescent system (Close *et al.*, 2009) [6]. The *luxA* and *luxB* genes encode α and β subunits of bacterial luciferase, the enzyme directly responsible for light production. The *luxCDE* genes code for enzymes involved in synthesizing the long-chain aldehyde substrate required for the bioluminescent reaction. The *luxG* gene encodes flavin reductase, which regenerates the reduced flavin mononucleotide (FMNH₂) used by luciferase. The complete *lux* operon from *Photobacterium leiognathi* was successfully transferred into the chloroplasts genome of tobacco (*Nicotiana tabacum*) leaves, resulting in the development of the first autonomously luminescent plant (Krichevsky *et al.*, 2010) [29]. Bacterial DNA gel blot analysis confirmed the stable integration of both the *aadA* gene and the *lux* operon into the chloroplast *LUX-rps12/TrnV* region. Further molecular analysis of DNA isolated from the transplastomic leaves confirmed the presence of plasmid-derived genes *TrnA*, *TrnI* and *aadA*, validating successful transformation. (Krichevsky *et al.*, 2010) [29].

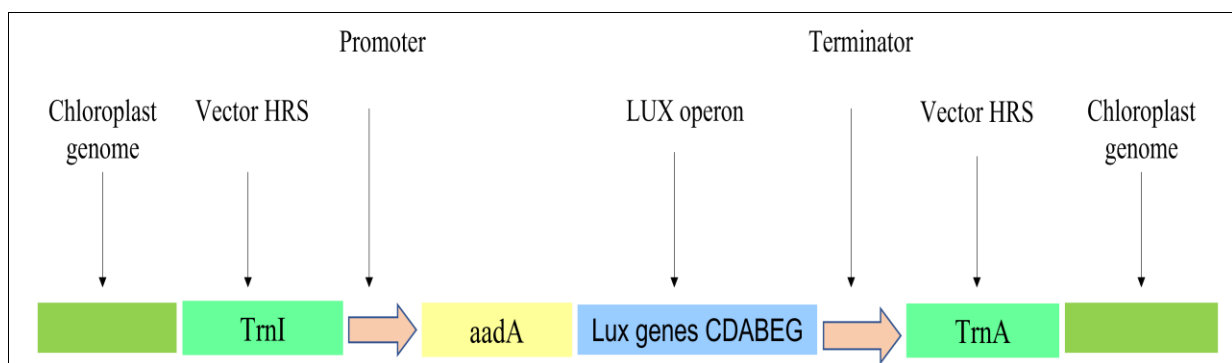


Fig 4: LUX-TrnI/TrnA transplastomic chloroplast genome

4. Fungal bioluminescent system

Recently; a newly discovered fourth bioluminescent system derived from bioluminescent fungi has recently been described. This system enables the generation of brightly glowing self-sustaining glowing plants and marks the first genetically encodable bioluminescent pathway derived from eukaryotes. The fungal bioluminescent system produce

emits light without causing cytotoxicity or growth inhibition in plant cells (Kotlobay *et al.*, 2018) [28]. This system is unique as it comprises a genetically encodable eukaryotic luciferase-luciferin mechanism, which has been successfully introduced into plant cells (Khakhar *et al.*, 2020; Mitouchkina *et al.*, 2020) [24, 32]. The luciferin biosynthesis pathway in fungi luciferin is known as the caffeic acid

cycle, a metabolic pathway naturally present in all plants. This cycle supports self-sustained bioluminescence that is visible to the naked eye, offering a distinct advantage as a biological light source.

To create transgenic tobacco plants (*Nicotiana benthamiana*) with advanced features a system was implemented that continuously expresses the fungal caffeic acid cycle, originally derived from the bioluminescent fungus *Neonothopanus nambi*. This system relies on four key enzymes that drive the caffeic acid cycle pathway: fungal luciferase (Luz), hispidin synthase (HispS), hispidin-3-hydroxylase (H3H), and caffeoylpyruvate hydroxylase (CPH).

Another essential enzyme is NPGA (4'-phosphopantetheinyl transferase) is required to activate HispS through post-translational modification (Ke and Tsai 2022). The tree fungus *Omphalotus olearius* is naturally bioluminescent and emits a bright glow at night (Farusi and Watt 2016) [12]. Similarly, the glowing transgenic plants express emitting light for these genes during all developmental stages. Most importantly these plants do not require any external substrate to produce a level of brightness that is easily visible to the naked eye. The self-luminescent tobacco plants were significantly brighter than previously reported self-light-emitting plants (Khakhar *et al.*, 2020) [24].

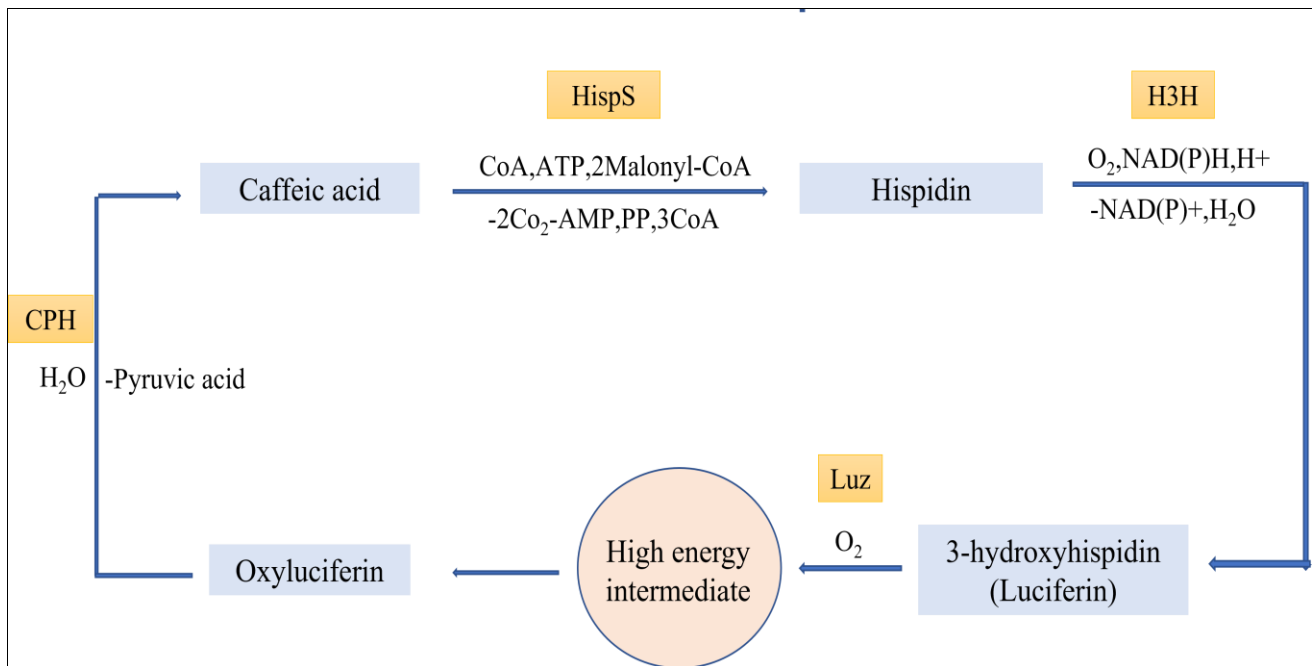


Fig 5: Fungal luciferin biosynthetic bioluminescence pathway

Working on the Caffeic Acid Cycle (CAC): The caffeic acid cycle is a native biosynthetic pathway found in all plants and does not appear to cause any harm. It is generally present in all plant cells. When used in the fungal bioluminescence system, the expression of the caffeic acid cycle is not-toxic to plants. This cycle primarily serves as the metabolic pathway responsible for synthesizing fungus luciferin. In the pathway, fungal luciferin is transformed into 3-hydroxyhispidin. The enzyme Luz (fungal luciferase) catalyses the oxidation of luciferin to produce photons (light) along with caffeoylpyruvic acid, which is subsequently hydrolysed into caffeic acid and pyruvic acid. The enzyme HispS (hispidin synthase), through post-translational activation can recycle caffeic acid to regenerate hispidin (Purtov *et al.*, 2015 and Oba *et al.*, 2017) [34, 37]. Additionally, the fungal caffeic acid cycle contributed to the synthesis of key intermediary plant metabolites including lignins, flavonoids (such as anthocyanins) and condensed tannins and shikimate (Mitiouchkina *et al.*, 2020 and Li *et al.*, 2021) [25, 32].

5. Protein bioluminescent system

In 1995, the green fluorescent protein (GFP) gene originally isolated from the jellyfish *Aequorea victoria* was successfully expressed in *Arabidopsis*, marking a novel advancement in the development of living glowing plant

cells (Hu and Cheng 1995) [20]. Protein modification particularly changes in the amino acid sequences of luciferase can result in significant shifts in the emission wavelength. The photoprotein responsible for fluorescence in *Aequorea victoria* is known as GFP. Fluorescent protein (FPs) have been engineered to emit across a wide spectral fluorescent range including yellow, blue, green, red, and cyan (Blatt and Grefen 2014) [2]. These FPs represent a practically significant group of light-emitting systems. Recently, some plants have been genetically modified to express bioluminescence systems with FPs contributing to the induction of most native luminescence (Kim and Paulmurugan 2021) [25]. FPs produce photoluminescence allowing them to glow without consuming ATP (Chudakov *et al.*, 2010) [5]. Bioluminescent systems produce light through the oxidation of a specific substrate in the presence of cofactors such as ATP and NADH catalyzed by the specific enzyme luciferase (Fleiss and Sarkisyan 2019) [13]. Both bioluminescent systems and FPs are valuable tools in plant biology serving as powerful biomarkers and biosensors in living plants cell metabolism. In *Aequorea Victoria* uses the bioluminescent protein aequorin excites GFP via radiationless energy transfer promoting electrons in FPs to an excited state. As these electrons return to the ground state, visible light is emitted (Rowe *et al.*, 2009) [38].

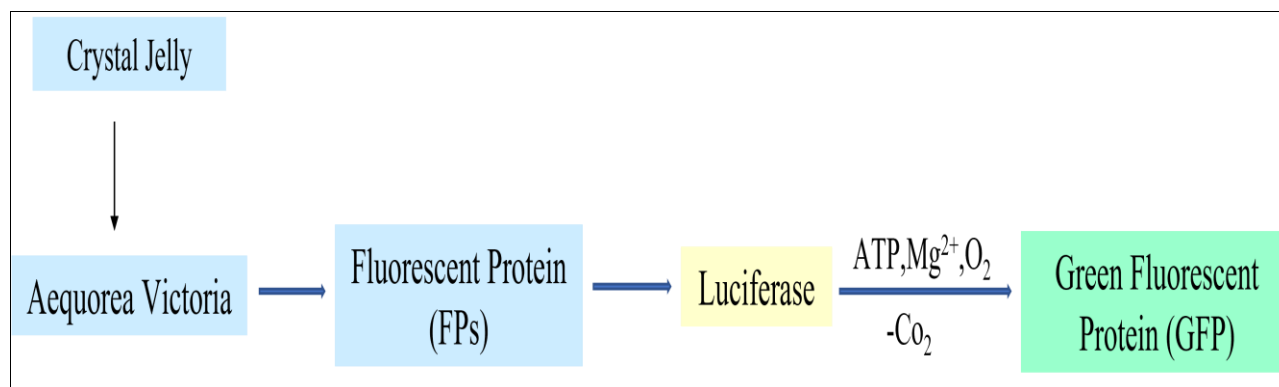

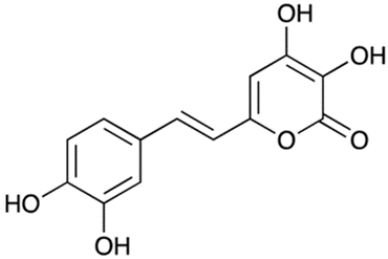
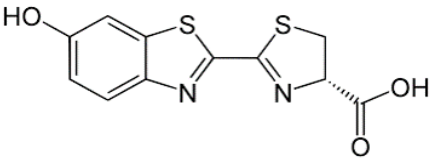
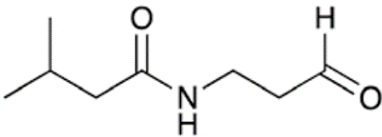
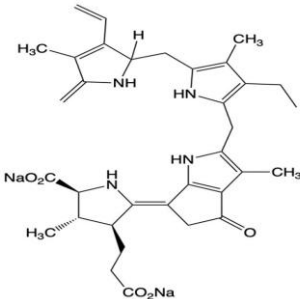


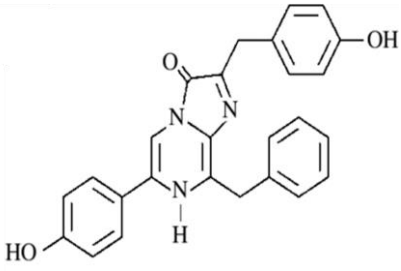
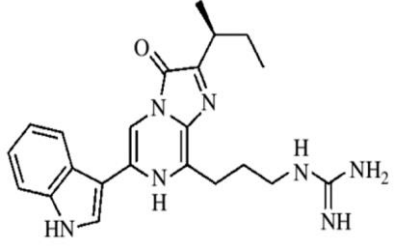
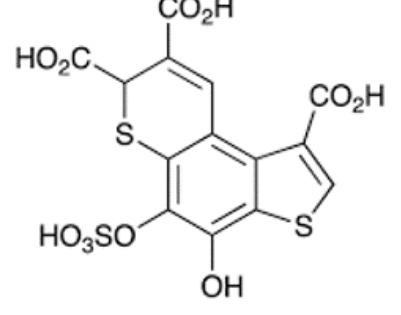
Figure 6: The mechanism of protein bioluminescent system

The protein based bioluminescent system includes two representative models: Nano luciferase (England *et al.*, 2016) ^[10] and the Nano lantern (Doerr, 2013) ^[7]. Nano luciferase is derived from the luciferase of the shrimp *Oplophorus gracilirostris* luciferase (Hall *et al.*, 2012) ^[19]. The Nano lantern is an artificial luminescent protein created

by fusing enhanced *Renilla reniformis* luciferase with a fluorescent protein (Saito *et al.*, 2012) ^[39]. Recently, a green enhanced fluorescence Nano lantern gene was introduced into *Arabidopsis thaliana* resulting in luminescence that was significantly brighter than that produced with the commonly used substrate furimazine (Furuhata *et al.*, 2020) ^[14].

Table 2: Molecular structure of the known Luciferin Genes

Bioluminescence Species	Luciferin	Luciferase Size	Wavelength
Bacterial luciferin		~ 75 kDa	490 nm
Fungal luciferin		~ 29 kDa	520 nm
D - luciferin		~ 280 kDa	560 nm
Diplocardia luciferin		~ 300 kDa	500–530 nm
Dinoflagellate luciferin		~ 135 kDa	476 nm

Marine luciferin		~ 20 kDa	480 nm
Cypridina luciferin		~ 61 kDa	452 nm
Odontosyllis luciferin		~ 35 kDa	510 nm

Diversity of Bioluminescent Systems: Bioluminescence has evolved independently more than 40 times throughout nature (Haddock *et al.*, 2010) ^[18], leading to a remarkable range of chemical mechanisms and variations in light

colours. This system exhibits significant diversity in both structure and function across different biological group reflecting the evolutionary adaptability of bioluminescence among organisms.



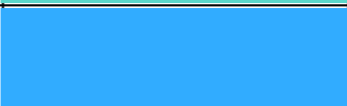
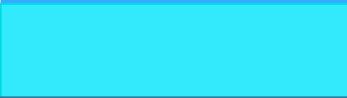




Table 3: Diversity of Bioluminescent Organisms and Their Mechanisms

Organism Type	Example Species	Emission Colour	System Type
Bacteria	<i>Vibrio fischeri</i>	Blue-Green	FMNH2-dependent
Fungi	<i>Neonothopanus nambi</i>	Green	ATP-independent
Insects	<i>Photinus pyralis</i> (firefly)	Green-Yellow	ATP-dependent luciferase
Marine organisms	<i>Aequorea victoria</i>	Blue	Photoproteins (i.e. aequorin)
Dinoflagellates	<i>Noctiluca scintillans</i>	Blue	Luciferin-binding proteins

Colours of Bioluminescence: In nature, bioluminescence produces various colours of light – mainly blue, green, red, yellow, orange, turquoise, and purple. Blue emission is the most common bioluminescent colour especially prevalent in marine organisms such as jellyfish, dinoflagellates, and deep-sea fish. Blue light penetrates water effectively making it ideal for communication and predation in oceanic environments. Green emission is found in some beetles and fungi. It is often associated with terrestrial organisms such as *Mycena chlorophos* and *Panellus stipticus* or with engineered systems expressing GFP (green fluorescent protein). Yellow to Orange emission observed in some fireflies and other insects. Variations in luciferase structure

among firefly species cause shifts in emission colour ranging from green to orange. Red emission light is extremely rare in nature. A notable example is the deep-sea dragonfish (*Malacosteus niger*), which can emit and detect red bioluminescence giving it a stealth advantage in the deep ocean. Turquoise bioluminescence characterized by light emission in the 475-495nm wavelength range is a captivating phenomenon with significant applications in bioimaging optogenetics and synthetic biology. Purple bioluminescence emitting light in the 400-420nm range is relatively rare in nature. This emission is typically achieved through specific luciferase-luciferin system engineered photoproteins or synthetic substrates.

Table 4: Emission Wavelengths of Bioluminescence in Various Organisms

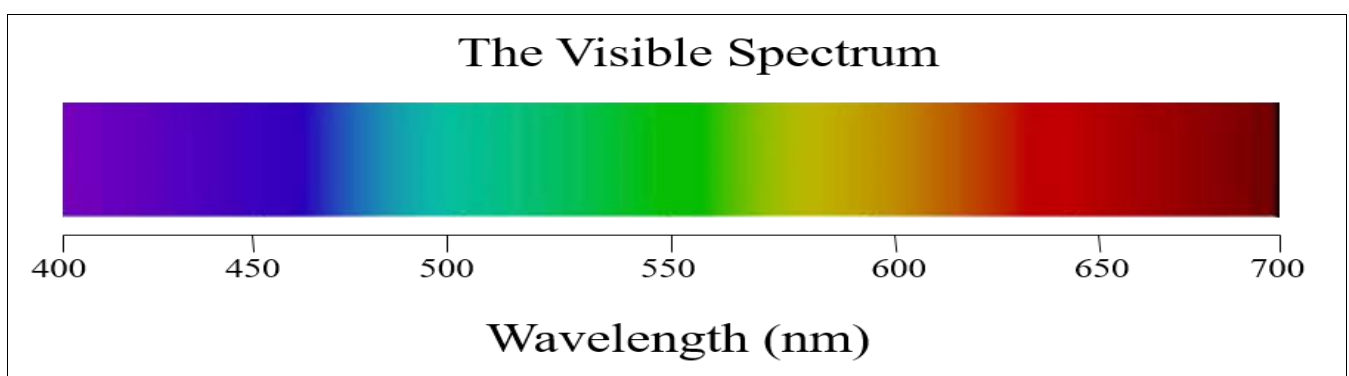
Luciferin	Luminescence maximum (nm)	Approximate colour	
Coelenterazine	400 nm	Purple	
	450-480 nm	Blue to Turquoise	
Dinoflagellate luciferin	474 nm	Blue	
Bacterial luciferin	490 nm	Turquoise	
Fungus luciferin	520-530 nm	Yellow	
Firefly luciferin	560 nm	Green	
	615 nm	Orange	
Deep sea dragonfish	750 nm	Red	

In India, over 100 species across various taxa exhibit bioluminescence including fireflies (*Lampyridae*), click beetles (*Elateridae*), and certain fungi. These organisms utilize bioluminescence for purposes such as mating communication and predation. Despite their ecological significance studies on their distribution and applications in

India are limited highlighting the need for further research in biodiversity and conservation (Chatragadda 2020) ^[3]. Certain fungi such as *Armillaria mellea* and *Mycena chlorophose* exhibit bioluminescence. This light emission is believed to attract insects thereby aiding in spore dispersal (Duchatelet and Dupont 2024) ^[8].

Table 5: Some Example of bioluminescent organisms

Organism	Common Name	Wavelength range of light emission
<i>Aequorea aequorea</i>	Jelly fish	~ 500-523nm
<i>Aequorea victoria</i>	Jelly fish	~ 520nm
<i>Diplocardia longa</i>	Earthworm	~ 500-530nm
<i>Gonyulax polyedra</i>	Dinoflagellate	~ 479nm
<i>Mycena mushroom</i>	Fungal	~ 520-530nm
<i>Odontosyllis luciferin</i>	Fireworm	~ 510nm
<i>Photinus pyralis</i>	Firefly	~ 530-590nm
<i>Pleurotus japonicus</i>	Moon night mushroom	~ 524nm
<i>Vibrio fischeri</i>	Marine bacterium	~ 489nm
<i>Malacosteus niger</i>	Deep sea dragonfish	~ 750nm



Applications of Bioluminescence Systems

- 1. Biomedical Imaging:** luciferase reporters are widely used in non-invasive *in vivo* imaging to track gene expression, cancer progression, and infection dynamic. Bioluminescence imaging (BLI) is a powerful technique used to monitor cellular and molecular processes in living animals. Luciferase-expressing cells or tissues can be tracked over time (Greer and Szalay 2002)^[17].
- 2. Biosensing:** bioluminescent systems are applied in environmental monitoring for detecting toxins, heavy metals, and pollutants. Whole-cell biosensors expressing luciferase genes respond to specific analytes with a light signal. Engineered microorganisms expressing bioluminescent gene can detect and respond to environmental contaminants including – Heavy metals (i.e. mercury, cadmium), Organic pollutants (i.e. toluene, pesticides), and Antibiotics in water sources (Van der Meer and Belkin 2010).
- 3. Synthetic Biology:** engineered systems using fungal or bacterial bioluminescence have been incorporated into plants, bacteria, and mammalian cells for real-time biological feedback and smart biosystems (Mitiouchkina *et al.*, 2020)^[32].
- 4. Sustainable Technologies:** bioluminescent systems are being explored for use in eco-friendly lighting especially in genetically engineered plants or algae as alternative to electricity-based lights in public spaces (Escher *et al.*, 2020)^[11].
- 5. Ecological Monitoring:** natural or synthetic bioluminescent organisms can be used to: Monitor ecosystem health and Track biogeochemical cycles in marine environments (Haddock *et al.*, 2010)^[18].
- 6. Engineered bioluminescence Plants and Algae recent:** innovations have enabled genetically engineered plants and algae to autonomously glow, potentially serving as: Living lights for sustainable urban design (Escher *et al.*, 2020)^[11] and Biosensors for plant health or environmental stress (Mitiouchkina *et al.*, 2020)^[32].

Use of Bioluminescence Plant in Society

One of the most significant applications of bioluminescence involves its use in living organisms such as bacteria, fungi, insects, and fireflies, where it serves as a natural light source. The main applications of bioluminescence systems include the study of antimicrobial drugs, tracking bacterial infections and environmental monitoring (Bjorkman and Karl 2001)^[1]. Fluorescent proteins can be used to create glowing flowers and fluorescent plant specimens. These fluorescent plants have potential as alternative light sources such as desk lamps or streetlight in decorative or eco-friendly settings (Dunuweera *et al.*, 2024)^[9]. Beyond illumination bioluminescent plants may also contribute to solar energy applications. With advancements in biotechnology, transgenic plants can now produce autoluminescence light enabling researchers to study environmental stress and plant metabolism in real time

through bioluminescence. Glowing plants could also be commercialized and distributed in the market, reducing reliance on conventional electricity and offering a more sustainable and economical solution for indoor and outdoor and outdoor lighting. Indoor lighting is essential for modern living yet it can be costly and environmentally harmful. Bioluminescence plants offer a promising eco-friendly alternative that addresses both economic and environmental concerns.

Use as a Sustainable Light Source in Future Prospective

In future possibilities; the production of transgenic bioluminescence plants could serve as an alternative decorative feature for buildings and public spaces. Engineered bioluminescence plants developed through synthetic biology to autonomously emit light without external energy input offer a promising nature-based solution for low-energy lighting. These glowing plants could function as ornamental streetlights or reading lamps that require no electricity. The light is generated automatically through the metabolism activity of the plants living tissues. This innovation has the potential to provide low intensity indoor lighting and transform plants or trees into self-sustaining light sources replacing traditional streetlights and pole lights. Such an alternative lighting source could contribute to large- or small-scale energy conservation efforts. These glowing plants also hold promise for reducing light pollution and promoting nature substitutes for artificial lighting to illuminate the night sky in a more sustainable way.

In this article, we provide an intentionally brief overview of emitting light reaction. Thus, they have done with many plants like kale, spinach, arugula, and watercress have been explored for their potential to emit light offering natural illumination suitable for reading and writing.

Sustainable Development in the Next Generation of Society

In the future; sustainable development will no longer remain just a concept – it will become an imperative for global well-being. Defined by the Brundtland Commission as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” it emphasizes the balanced integration of economic growth environmental protection and social equity. Bioluminescent plants could play a significant role in this vision. Farmers can cultivate these plants as a novel source of income. Additionally, they can be used as ornamental plants primarily for decorative purposes. These glowing plants will not only be a remarkable outcome of scientific research but also offer new avenues in the field of biotechnology. Due to their uniqueness and aesthetic bioluminescent plants may be considered high value ornamental items contributing to the economy. Their cultivation and commercialization could benefit farmers economically while also reducing electricity consumption – an environmentally friendly advantage. As the next generation faces intensifying challenges such as climate change, resource depletion, biodiversity loss, and social inequality sustainable development must move beyond policy and become an integral part of practice across all sectors of society.

Conclusion

The concept of bioluminescent plants represents a visionary intersection of synthetic biology, environmental design and sustainable innovation. Bioluminescence is a natural process of light emission that occurs in the presence of oxygen. Light can be produced in living organisms by transferring bioluminescent genes. This has been achieved by incorporating genes from various sources such as bacteria, fungi, insects, firefly, marine organism, algae, dinoflagellate, jellyfish, earthworm, and sea star fish to the living organism. By integrating natural light producing pathways into plants systems, researchers are exploring the potential for creating living, self-sustaining sources of light that operate without external electricity or chemical inputs. These genetically engineered plants could significantly contribute to energy-efficient urban lighting, eco-friendly interior design and real-time environmental monitoring, aligning closely with the core principles of sustainable development. In recent years, several bioluminescence systems have been developed including the luciferase-luciferin system, PBIN technique, bacterial bioluminescence system, caffeic acid cycle (CAC) and fluorescent proteins (FPs). Each of these technologies enables the transformation of ordinary plants into glowing ones that are visibly luminescent to the naked eye.

This review, highlights the role of bioluminescent systems and provides a concise summary of the major techniques used to create bioluminescent plants offering a helpful resource for new researchers in the field. As genetic engineering continues to advance bioluminescent systems are expected to play an increasingly significant role in the development of next generation bio-integrated technologies.

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