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Effect of artificial light on plant ecology and physiology: A review

MAMTA BAJYA¹, TEJPAL BAJAYA^{2*}, RAVNEET KAUR¹, SALEEM JAHANGIR DAR¹ and SURESH YADAV³

Punjab Agricultural University, Ludhiana, Punjab 141 004, India

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ABSTRACT

Early in the 20th century, introduction of artificial light has caused a significant change in human developmental process, but use of artificial light in night has also produced negative effect on phonological, physiological and ecological responses which are sustained in the plants, animals and microorganism from millions of years. In these consequences, most of the plant processes under ANLP are affected intensely and cause compelling changes in plant life cycle from germination to maturity. However, severe effects were observed in the case of pollination, photoreceptor signalling, flowering and microhabitats of plants. Along with, drastic effects on ecology and environments, its relevance to human developmental processes cannot be avoided. Therefore, we need to equipoise between sustainable environment and steady human development processes. Further, selection of plant/crop species, which are more responsive to artificial night light pollution, can minimize the ecological consequences of night light pollution. Likewise, changing artificial nightscape with the implication of new Light emitting diodes lightening policies like Ujala, which are low cost, more durable, eco-friendly and less emitter of CO₂, have potential to overcome the biodiversity threat, which arises due to the old artificial lightening technology, used from decades. Hence, adopting new advanced artificial lightening technology and understanding its impact on plant ecosystem will be a future challenge for plant biologists. However, drastic effects of artificial light during night time are enormous; therefore, the present topic is focused on the physiological and ecological consequences of artificial night light pollution on plant systems.

Keywords: Artificial light, Artificial night light pollution, Diurnal cycles, Microenvironment, Photoperiodism, Photoreceptors, Phytochrome

Life on this planet originated million years ago, through a continuous and complex evolutionary process. In this process, light played as a crucial factor in sustaining life on this planet. Cyanobacteria was the first evolved organism on this planet, having capacity to utilize sun's energy in photosynthesis for producing food for its own. Light acts as resource via photosynthetic pathway or via light signalling mechanisms (Gaston et al. 2013). As evolution occurs, plants develop complex and huge number of pigment systems to absorb certain wavelengths of light spectrum. Along with pigment systems, plants also develop diverse photoreceptors, that sense and provide signals for diurnal regulation of growth and hormonal functions. Light attributes such as quality, intensity and direction, also have significant effects on regulating various processes like seed germination, seedling development, photosynthesis, photomorphogenesis, photoperiodism, circadian rhythm

and seasonal phenology changes in plants. It has been well reported that diurnal cycles in plant have been evolved through the adaptation or acclimatization over the period of million of years (Xu et al. 2015). On the other hand, artificial light causes adverse effect on the living organisms called photopollution. Modulation of night naturally glows by the anthropogenic sources of light is referred as Night light pollution. Plants growth and development is controlled by simultaneously identifying and responding to both the external and internal signals. One well-studied example is the hypocotyl elongation of young seedlings. The light inhibition that provokes the hypocotyl elongation is controlled by the red/far-red light receptor phytochromes and phytohormones, including brassinosteroids (BR), auxin, gibberellins (GA), cytokinins (CK), ethylene, and abscisic acid (ABA). Phytochromes and phytohormones interact to control growth. Multiple genetic studies have proposed that light directly affects the cellular level of some phytohormones and the signal transduction of the vast majority of phytohormones also affects photoreceptor signal transduction. Signal transduction involves the transmission and the conversion of extracellular to intracellular signals into cellular responses where light plays the pivotal factor and can regulate plant growth. Phytochromes are the most

¹Punjab Agricultural University, Ludhiana, Punjab; ²Sri Karan Narendra Agriculture University, Jobner, Rajasthan; ³ICAR-Indian Agricultural Research Institute, New Delhi. *Corresponding author email: tejpalbajya93@gmail.com

important sensors in plants, belonging to a gene family of photoreceptors. They are a family of chromoproteins with a linear tetrapyrrole chromophore. They have two photointerconvertible forms; the Pr and the Pfr. Pr absorbs red light in a wavelength approximately 667 nm and is afterward converted to Pfr. Plants use the phytochromes to grow in difficult times such as shading and moving toward light. PHYB is the significant contributor to germination when seeds have missed low-temperature imbibition. The natural celestial sources mainly the moon, airglows, stars, milky way, and zodiacal lights is responsible for natural lightening levels (Sky glow) while artificial light scattering more light that is responsible for artificial sky glowing during night times (Cinzano et al. 2001). The high-resolution satellite data shows that more than 66% world population is living in the night light polluted areas and unfortunately in the case of Singapore and San Marino, this value is near to 100% (Table 1). Artificial night light pollution (ANLP) is rising approximately 6% per year, with increasing use of artificial light (AL) sources and posing a major threat in urban environment. In coming decades, there are chances of expanding the polluted bright habitats such as roadside border, fences, security lightening, street lightening, vehicles lightening, and domestic gardens (Tikka et al. 2001).

Many natural or semi-natural habitats are enlightened with direct AL from the vehicle headlights or roadside street lamp lighting at night that has potential to modify the plant physiological behaviour processes and ecological responses of plant systems (Kyba et al. 2015) and disrupt the predator-prey relationships, insect courtship, plant-animal interactions, seasonal oestrus cycle, food consumption pattern and sleeping behaviours in living being. For any given organism, the impact of AL may be neutral, beneficial and detrimental and modulating in food webs of stable ecosystems, posing public health issues, and huge wastage

of energy and money (Macgregor *et al.* 2015). Most of the earlier findings on ANLP were mainly focused on the animal system and ecosystem sustainability, but the studies regarding plant systems were limited. Therefore, the objective of this review paper is to compile the diverse plant diurnal processes and pathways under the control of light and the effect of artificial light on various physiological, behavioural and ecological functions of plants.

Diurnal Cycles

Sun light is considered as an essential environmental abiotic factor in the regulation of plant growth and development by diverse photoreceptors for the sensing and monitoring of light. Through photosynthetic processes, light energy is captured by autotrophs and cycled through diverse stable food webs to control the miscellaneous plant physiological and behavioural functions from seed germination to seed maturation stages (Millar 2016). It also has administrative role in the circadian rhythm, metabolic rhythm, leaf development in tomato, rhizosphere development in Oca (Oxalis tuberosa), tuberization and flowering in potato, chloroplast movement in fern, stomata movement in maize and stem expansion in Brassica juncea (Murata 1969). The switching from photoautotrophic to heterotrophic metabolism between diurnal cycles, interactions occurs through the temporal separation of storage compound synthesis and their mobilization (Wijnen et al. 2006). Various roles of light and dark period on growth and developmental processes are enlisted in Table 2.

Ecological night light pollution

Sky glow may be defined as reflection of light from sky especially during night time. Ecological light pollution includes, chronic or periodically increased illumination, unexpected changes in night illumination and direct night

Table 1 A list of most night light polluted countries in the world representing percentage of population and area coming under brightness>3000 μcd/m² night sky and approximate ranges of light brightness (μcd/m²) in metro cities during night time

Country	% Population under brightness	Country	% Area under brightness	Name of city	*Average range of light brightness
Singapore	100	Singapore	100	Washington, D.C. (US)	10600-23000
Kuwait	98.1	Gibraltar	28.6	Tokyo (Japan)	9800-22500
Qatar	96.7	Malta	16.7	Doha (Qatar)	9500-16700
UAE	92.7	Qatar	16.3	Kuwait city (Kuwait)	9300-15900
Saudi Arabia	83	Kuwait	11.5	Moscow (Russia)	8400-15200
South Korea	66.4	Israel	8.1	London (UK)	8100- 14600
Israel	61	Netherland	7.2	Osaka (Japan)	8100-14300
Argentina	57.7	UAE	5.7	New York (US)	7400-11600
Libya	52.7	Trinidad and Tobago	5.2	Abu Dhabi (UAE)	7200-10900
Trinidad and Tobago	50.2	West bank	4.1	Vatican city (Vatican city)	7000-8900
Russia	32	Russia	0.1%	Paris (France)	6800-8200
India	5.9%	India	0.1%	New Delhi (India)	5100-6900

^{*}Ranges for light brightness in metro cities are approximate value, it changes according elevation, latitude and longitude of a particular place. (10; Visible Infrared Imaging Radiometer Suite (VIIRS) 2017 map; https://www.lightpollutionmap.info).

Light

Table 2 Function of light and dark period on various growth and developmental processes of plants life cycles

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Seedling development (Millar 2016):

Seed germination, Seedling photo-morphogenesis, formation of new cell of hypocotyls, development of root, root hair and cotyledons and its expansion, cell autonomy, cell to cell interactions, unhooking, separation of the cotyledons, phototropism, plastid development and inhibition of hypocotyls elongation.

Photosynthetic processes (Von Arnim and Deng 1996):

Synthesis of chlorophyll, pigments excitation, electron transport chain, activation of Calvin cycle and chloroplast enzymes, photophosphorylation process, photolysis of water, and photorespiration processes

Flowering (Blanchard and Runkle 2010):

Period and time flowering, and number of flowers

Photomorphogenesis (Murata 1969, Whitman et al. 1998):

Phytohormonal regulated phenomenon photoperiodism, photothermoperiodism, Phototropism, root and shoot; leaf growth and circadian rhythm

Other activities: Mineral absorption, food translocation, assimilate partitioning, transpiration, plant defence and stomatal control in plants

Seedling development (Millar 2016):

Seed germination, seedling photo-morphogenesis, rapid stem elongation, distinct apical hook or coleoptiles synthesis; reduction in leaf growth, leaf etiolation, stems expansion, root elongation and lateral root growth during seedling development.

Dark

Metabolic fluxes (Wijnen and Young 2006):

Carbon skeleton for N assimilation, temporal metabolism of organic compounds, sulphur assimilation, mitochondrial antioxidant, defence mechanisms, starch degradation, protein degradation, repairing photo-oxidation and photo inhibition damage, and maintenance respiration

Flowering (Lin 2002):

Nocturnal pollinations, number and types of pollinators

Photomorphogenesis (Murata 1969, Whitman et al. 1998):

Phototropism (seedlings, petioles, and inflorescence) root and shoot; leaf growth and circadian rhythm

Other activities: Stress recovery, assimilate partitioning, phytohormone regulation, stomatal control and sleep movements in plants

sky glow. There are various sources of ecological light pollution which include sky glow, lighted buildings, garden and towers, advertising lighting, architectural lighting, street lights, fishing boats, security lights, lights on vehicles, flares on offshore oil platforms and even lights on undersea research vessels, all of them have the potential to disrupt the ecosystems at the varying degrees. Variation in levels of luminance from different artificial sources ranges from urban sky glow (0.15 lux), full moon (0.1-0.3 lux), residential street light (5 lux), roadside street (15 lux), most home (100-300 lux), office (400-600 lux), cloudy day (1000-10000 lux), partly sunny (50000 lux) and for full sunlight (103000 lux) (Cheung et al. 2014). Sunlight spectrum is mainly enriched with 400-700 nm wavelength (PAR photosynthetically active radiation) peak at blue and red region, which is important for regulation of diverse phenomenon on earth while the artificial light sources are differing in emission spectrum compared to sunlight and moonlight. Therefore, artificial light during night time modulates normal plants light signalling processes and causes drastic changes in plant physiological and ecological functions.

Effects of night light pollution on plant physiological and behavioural functions

Artificial night light pollution is a well reported environmental phenomenon. Plant scientist and horticulturist are very much familiar about detrimental effects of luminous street lighting on trees. The results of the use of controlled continuous light (CL) on plants showed increase in growth, daily carbon gain, antioxidant production, and productivity in tomato (Matzke 1936), but they also have some negative impacts on several plant species such as reduction of

nitrate content in Lettuce, increase in vascular pattern complexity (Kaur 2018) and this complexity further causes fruit cracking in lemon (Kaur *et al.* 2019). Moreover, it causes lower photosynthetic parameters like reduction in photosynthetic capacity at saturating light, quantum yield, RuBisCO carboxylation and electron transport (Mundiyara *et al.* 2017). Other harmful effects of CL on plant growth are well known, but the knowledge of ANLP on plants is very few in number. Some effects of ANLP on plant physiological, ecological and behavioural functions are discussed in Table 3.

Light perception by photoreceptors

Various photoreceptors like phytochromes, phytotropins, cryptochromes, UV-Band green light receptors have been evaluated in plants to sense different wavelengths and signalling various light mediated functions:

- (a) *Phytochromes*: Phytochromes are sensitive to red light and far-red light of visual spectrum. Phytochrome exists in two photo inter-convertible forms, a biologically inactive P_r, which upon absorption of red light is converted into a biologically active form P_{fr} and P_{fr} is converted back to P_r on absorbing far-red light. Phytochromes have important role in the resetting of biological switch and initiation and termination of photo-morphological processes (Lymperopoulos *et al.* 2018).
- (b) Cryptochromes: Cryptochromes are a class of flavoproteins that are sensitive to blue light. They are involved in the regulation of circadian rhythms of plants, animals and bacteria. The two genes cry 1 and cry 2 encoding for protein CRY 1 and CRY 2 have an important role in regulation of phototropism, stem, cotyledon, leaf

Phenomenon Function altered/change Mechanism References Phytochrome signalling Reduces the flower transition time and Change in Pr/Pfr inter-conversion Dorais and Gosselin (2000) induction or prevention of flowering Delaying or advancing the cycles and Circadian cycle Entrainment/masking, phase shifting Holker et al. (2000), Murata susceptible to frost damage (1969)Dark recovery from Clover foliar injury, high photo Reduction in dark recovery period, Ahmad et al. (1998), Gautam stress inhibition, photo oxidation, oxidative reduced day and night temperature et al. 2015 stress, UV light stress, DNA damaging, difference and vapour pressure wilting and high nigh temperature Photosynthesis Lower photosynthetic rate, quantum Reduction in chlorophyll and nitrogen Vollsnes et al. (2009), yield, electron transport chain and content Von Arnim and Deng (1996) alteration in PSII activity Metabolic fluxes Starving of carbon and nitrogen Possibly high maintenance of Murata 1969, Queval et al. respiration Yield Shortening growth stages and Gautam et al. (2015) Increase, no changes or reduces alteration in yield parameters Pollination and Threatening to nocturnal and diurnal Habit fragmentation, changes in Macgregor et al. (2015) flowering pollinator, promotion or inhibition of natural pollination and reduced flowering population of nocturnal insects Food web Changes in the lavishness of parasites, Effect on top to down and vice-versa Oke (1973) predators and herbivores Microenvironment and Adaptation, acclimatization or fitness Change in surrounding environment Blanchard et al. (2010) and ecology evolution of present or future generation

Table 3 Effect of artificial night light pollution on plant physiological and ecological functions

- expansion, flowering, photomorphogenesis, circadian rhythm and magneto reception in plants (Whitman *et al.* 1998). Red Light emitting diodes (LEDs) combined with blue LEDs light, activates the cryptochromes and phytochromes that regulate plant growth and development (Lin 2002).
- (c) Circadian clock: The daily cycles of day and night, seasonal changes, and the monthly lunar cycles control many physiological and behavioural functions in plants and animals. Artificial light after dusk or prior to dawn, can cause phase shifting in the circadian rhythm, by delaying or advancing the diurnal cycles. Artificial light during night time can affect the diverse circadian processes like pulvinar leaf movements, stomatal behaviour, cell elongation, elongation rate of the abaxial and adaxial cells of the petiole, rearrangement of guard cell cytoskeleton, control of stomatal aperture and gas exchange, CO₂ assimilation in CAM plants, auxin levels and transport and ethylene production in plants (Ahmad et al. 1998).
- (d) Dark recovery from stress: It has been suggested that continuous periods of darkness, are very critical for the regulating diverse physiological and behavioural functions in living beings, including plants. Dark period is very crucial in plants, for resource, repairing and recovery from the environmental stresses, which are exposed during day times. Recent studies showed that continuous artificial light (approximately 74 lux) can significantly increase the foliar injury in clover due to Ozone (Ahmad et al. 1998). In the recent years, introduction of excess artificial light in environment is

- responsible for reducing day-night relative humidity and temperature differences, which can alter fruiting and boll development in cotton, seed set, seed quality and yield in rice and other crops (Gautam *et al.* 2015).
- Photosynthesis and Metabolic fluxes: The ecological impacts of night time light pollution have been a longstanding source of concern, accentuated by realized and projected growth in electrical lighting. As human communities and lighting technologies develop, artificial light increasingly modifies natural light regimes by encroaching on dark refuges in space, in time, and across wavelengths (Mundiyara et al. 2017). A wide variety of ecological implications of artificial light have been identified. However, the primary research to date is largely focused on the disruptive influence of night time light on higher vertebrates, the subject is in need of synthesis within a common mechanistic framework. In green plants, light is absorbed for the photosynthesis process by the chlorophylls and carotenoids at wavelengths range between 400 and 700 nm (Vollsnes et al. 2009). Experiment regarding night interruption (4 h) by different light intensity in Cymbidium orchids (variety Red Fire and Yokihi) showed that photosynthesis rate, actual quantum yield and electron transport rate were lower in the case of high night interruption (HNI) compared to control and LNI (Low night Interruption) conditions in both cultivars. The plants grown under HNI conditions have lower chlorophyll and nitrogen contents than those under control and LNI conditions (Darko et al. 2014).
- (f) Yield: A study conducted to know the effects of ANLP by

using high pressure sodium lamp (HPS) (roadway light) in soybean crop observed that even as little as 2 to 8 lux light intensity can reduce the crop yield by 20–40% due to delayed flowering and ripening. Exposure to night time illumination, particularly from HPS street lighting may result in disruption of the plant's shoot growth, flowering, and leaf expansion and abscission and bud dormancy. In temperate climates, this makes the plants more susceptible to frost, fungal infections, and insect infestations. However, it might be possible that ANLP improves yield or biomass production in some LDPs crops by advancing day length, but it may cause much detrimental effects on the yield of short duration economically important agricultural crops (Raven and Cockell 2006).

Effect of night light pollution on ecosystem and ecology

The cumulative effects of behavioural changes induced by ANLP on competition and predation have the potential to disrupt key ecosystem functions. Effects of ANLP on some ecological processes are described here.

- (a) *Primary production*: Primary production is the key ecosystem process, controlled by the light. It is reported that the tree and shrub exposed to street lamps may have longer growing periods i.e earlier leaf-out and later leaf-fall times than those in darker environments. Night light pollution has marked effect on photosynthesis of aquatic communities including photosynthetic algae, mosses and ferns (Kim *et al.* 2013). Thus, effect of artificial night light pollution can disrupt the equilibrium state of a stable ecosystem.
- (b) Pollination and flowering: Nocturnal insect pollinators including moths and diurnal pollinators, face many threats as habitat fragmentation, climate change, and agrochemical uses in recent years. The flowers of Selenicereus grandiflorus (Queen of the Night) are fully open for two hours only at night. Prior to widespread use of outdoor electric lighting, the night sky was a stunning view with several thousand stars visible on a clear moonless night. But, with the increase in lighting to provide safety, security, advertisement and aesthetics, light pollution has grown to be a vexing problem. Today, our earth is wrapped in a luminous fog called skyglow caused by artificial lighting reflecting off airborne water droplets and dust particles that obscure much of the heavens from view. As a consequence, 25% of us can no longer see the Milky Way. Much of the provided artificial light is so bright and inefficiently directed that its use has negative effects. One of the harmful effects of excessive night lighting is the tremendous waste of energy and the environmental damage associated with producing electricity from mining, drilling, refining, combustion, and waste disposal. For example, it is estimated that 30% of the electricity generated for outdoor illumination is simply squandered by being misdirected into the sky. The International Dark-Sky Association estimates this wasted electricity costs \$1.5

- billion annually and results in 12 million tonnes of carbon dioxide in its generation. Many roadways and high-traffic areas are so intensely lit that visibility is actually reduced due to glare and poorly shielded fixtures. Another negative impact is that the annual cycles of growth and reproduction in trees controlled by day length can potentially be altered by supplemental night lighting. Increasing the artificial lighting conditions around them prohibit the flowering and reproduction (Chaney 2002).
- (c) Food Web: It was observed that the light during night increase the body mass, by shifting time of food intake, in micro fauna. Artificial light during night time changes in the abundance of parasites, predators and herbivores by the change in the population of host, prey species and primary producers through top-down effects (Oke 1973).
- (d) Microenvironment or Microhabitat: An individual plant or animal species have their fixed niche to stabilize their population and reproduce. Introduction of artificial lightening into environment generates heat and CO₂ resulting in the change of microenvironment. Meanwhile, in future if artificial lightening increases, it can reduce the day night temperature differences, which is essential for plant growth and development. High night temperature in rice showed the drastic effects on respiration, membrane stability, antioxidant capacity, and yield parameters (Blanchard and Runkle 2010).
- (e) Evolution: Artificial light has produced a significantly change in feeding behaviour of animals. Ultimately, any behaviour, which could be altered by artificial light and are under genetic control could allow artificial light to change the evolution of a species, like web formation in spider, predator- prey interaction, daily rhythm, pollination, reproduction, melatonin content and biological fitness (Halaj and Wise 2001).

Benefit and cost

Although widely discussed, the negative impacts of the ANLP on human health, ecosystem and ecology remains to be fully understood but the incorporation of artificial light in the environment also have some significant benefits like reduction in vehicle accident by 30% crime reduction, aesthetics and tourism (Mohammed and Tarpley 2009). It also benefitted to migratory birds in areas those are continuously illuminated foraged for longer periods and were able to locate food by sight. The advantages of using LEDs technology as artificial light source for plant growth applications were reported in many crops and flowers such as lettuce, pepper, wheat, spinach and banana.

Worldwide, grid-based electric lightening has been estimated to account for the 19% of electrical power production and energy consumed to supply lighting generates 1900 MT $\rm CO_2$ per annum, with cost \$360 billion, which are roughly 1% of total global GDP (Gross Domestic Production) (IEA 2019). Most inefficient incandescent lamps are large emitters of $\rm CO_2$ and above combined uses provide

only the 1% of global lighting but it is responsible for 20% of CO₂ emissions. In an era of tight oil markets, they consume 3% of world oil supply more than the total output of Kuwait (Lvanko *et al.* 2010). Therefore, Implication of new advance LEDs policy and understanding the mechanism and effect of artificial lightening are crucial for reducing night light pollution deleterious effects. Likewise, in India, implication of new scheme like Ujala (Unnat jyoti by affordable LED for all) distributed 18.78 Cr LED bulbs, saved 24391 million KW energy, 9757 Cr rupees and 19.7 MT CO₂ per (www.ujala.gov.in). Adoption and implication of scheme like UJALA in other countries may manage night light pollution and reduce disastrous effect on ecosystem.

Conclusion

It has been argued that the biological world on this planet is organized by the light. Artificial light is common characteristic of human settlement and transport networks. The extents of ecological night light pollution are global and increasing rapidly, throughout the world. Increase in demand also will cause more detrimental effect on ecosystem. Along with this, change in intensity, spectrum, and composition characteristics of artificial lighting worldwide; alter the microhabitats of plant and animal systems, which are sensed and adapted by living being from millions of years. Different light regimes are characterized as changes in the spatial distribution, the timing or in the spectral composition. Change in artificial lightning may reshape species interactions, community structure, and presumably associated with ecosystem functions and processes. Furthermore, effect of vehicle light, street light and various artificial lightening on SDP, tropical plant species, cross pollinated species are more crucial than self-pollinated and LDP. In this review paper, we have discussed various issues regarding plant physiological and ecological processes and responses, which are sensitive to diurnal cycle's changes. Therefore, in this new era of climate change, the area of night light pollution is growing as thrust area not only for animal and human being but also for the plants/crops in aggregation and becomes a challenging area, to be more studied in future.

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