REVIEW ARTICLE

Environment-Pathogen Interaction in Plant Diseases

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Abstract

The environment is an important aspect of plant ecology. And global environmental change is of major concern that is caused by natural and human activities which alter greenhouse gas concentrations in the atmosphere. An increase in the concentration of greenhouse gases is foreseen to continue to raise the average global temperature. Elevated concentration of carbon dioxide with increased temperature influences the plant-disease interactions. The environment influences the development as well as temporal and spatial dissemination of plant diseases. The result of a change in environment can either be favorable, non-favorable or impartial, as these changes can either lessen, expand or have no influence on diseases as each disease may be attributed differently to these variations in accordance to an area or time of year. Variation in environmental conditions is said to be influencing plants in natural ecosystems all around the world and change in climate directly impacts crops, along with their synergy in accordance with the microbial population. The important elements governing magnification and spread of plant diseases are temperature, moisture, light, and carbon dioxide concentration. Environment change causes a significant impact on germination, reproduction, sporulation, spore dispersal, along with perforation by pathogens as a pernicious pathogen will not invade a vulnerable host if the environmental conditions are not facilitative for the disease. The environment influences all life stages of host as well as that of a pathogen and as a result, induces an opposition to various pathosystems. Resistance mechanisms of plants, including effector-triggered immunity (ETI), pattern-triggered immunity (PTI) and defense network of hormones, are particularly influenced by environmental elements. Pathogenic virulence mechanisms like fabrication of virulence proteins and toxins, and also spore germination and survival are governed by factors such as atmospheric carbon dioxide, temperature, and humidity. A large number of *in-vitro* experiments to understand interactions between plants and pathogens rely on predetermined pathosystems by making use of ascertained environmental conditions which take into consideration relatively small part of vital plant–pathogen–environment interactions occurring in a natural ecosystem. Thus, there is a need to research effectiveness of disease management strategies that is, to assess current management strategies to understand the multifaceted nature of environment-pathogen interactions for the production of crops that are irrepressible to environmental change.

Keywords: Effector triggered immunity (ETI), Emergence diseases, Environment change, Microbe-or-pathogen-associated molecular pattern (MAMP or PAMP), Pattern triggered immunity (PTI), Plant-pathogen–environment interactions.

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Introduction

Human undertakings are generally credited to enhance the rate of global environmental changes that directly impact the bionomics**.** Greenhouse gases involving, carbon dioxide (CO_2), Methane (CH_4), water vapor (H_2O), nitrous oxide (N_2O), Ozone (O_3), and hydrofluorocarbons (HFCs) present in the atmosphere trap solar radiation to increase the surface temperature of the earth (Mahato, 2014). Pathogens that are known to infect plants are manifold, fluctuating from intracellular viruses and bacteria to extracellular, fungi, and nematodes. Based on the mode of nutrition, pathogens are classified as biotrophs or necrotrophs. Biotrophs are the organisms which attain nutrients from living cells of the host, whereas necrotrophs are known to kill host cells. Also, there is an abundance of hemibiotrophs, which show an initial biotrophic phase before finally killing the host. Change in environmental factors has an impact on the emergence of plant diseases in accordance with water, air, and soil pollution caused by human activities (Regniere, 2012). According to Inter-governmental Panel on Climate Change (IPCC, 2007), the planet earth is confronting an environment change, and atmospheric CO_2 has increased by as much as 30% and temperature by 0.3 to 0.6°C. Plants and pathogens are not known to interact in isolation. The 'disease triangle' concept in plant pathology characterizes the interaction of both plants and pathogen with the environment.

The global environment is known to be influenced by an abundance of factors and has a direct impact on all three constraints of disease triangle, involving, pathogen, host, and environment (Legreve and Duveiller, 2010). Due to environment change, pathogens are presented with short life cycles; as a result, the reproduction rate is increased, and the dispersion structure responds quickly. (Coakley *et al.,* 1999).

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Elevated temperature and CO_2 concentration have an influence on plant-disease interaction as it enhances the chances of diseases such as blast *(Magnaporthe grisea)* and sheath blight *(Rhizoctonia solani)* of rice (Kobayashi *et al.,* 2006). Crop growth and productivity can be affected due to high temperature and atmospheric CO_2 concentration in accordance with the availability of water (Rosenzweig and Tubiello, 2007, Ghini *et al.,* 2008, and Chakraborty and Newton, 2011). For disease to transpire, susceptible plant host, virulent pathogen, and a favorable environmental conditions are needed, as the absence of favorable conditions or any of three factors will result in dereliction for the disease to develop (Stevens, 1960). The impact of environmental constraints (e.g., high temperature) on pathogens and plants can have a positive, neutral, or negative impact on plant disease development. Both pathogens and plants have a prerequisite environmental condition for their magnification and reproduction. The more the environmental conditions vary from this 'disease optimum', the lesser disease symptoms will present themselves on the plant.

Host-pathogen-environment interactions:

The interaction between host, pathogen, and environment is nonspatial, ranging in order of interactions which completely facilitate the disease to those in which a susceptible plant is not infected at all. Environmental variables are known to have a significant impact on a host plant's substantial state, such as, its expansion, resistance mechanisms in accordance to biotic/abiotic stress response, along with a pathogen's survival, germination, and production of virulence proteins. These ever-changing environmental criterions can result in a host plant being fully vulnerable to being fully resistant, whereas the pathogen, on the other hand, ranges from being severely virulent to being weakly pathogenic.

Impact of atmospheric carbon dioxide concentration on plant diseases

- Elevated atmospheric CO_2 concentration enhances photosynthesis, water use efficiency and lessens the damage incurred from ozone (von Tiedmann and Firsching, 2000), also plant height and yield of crop increases significantly at higher concentrations of CO_2 (Eastburn *et al*., 2011).
- Increased concentration of atmospheric CO_2 levels results in an increase in overall leaf area, numbers of leaves, size of plant organs, leaf thickness, also the diameter of stems (Bowes, 1993 and Pritchard *et al*., 1999); as a result, host resistance is elevated (Coakley *et al*., 1999).
- Consequently, higher leaf area index favors the occurrence of *Stemphylium* blight, powdery mildew, rust, and *Alternaria* blight. Higher levels of CO_2 concentrations result in the production of more fungal spores. As a result of elevated atmospheric CO_2 concentration opening of stomata is also reduced leaf chemistry is modified, resulting in less disease incidence (Mcelrone *et al*., 2005). For example, in soybean, the enhanced concentration of O_3 and CO_2 modified the incidence of three soybean diseases, which are downy mildew *(Peronospora Manchuria),* brown spots *(Septoria glycines)* and sudden death syndrome (Eastburn *et al*., 2010).
- Barley plants with increased CO_2 concentration accumulate silica and produce papillae at the site of appressorial penetration by *Erysiphe graminis* (Hibberd *et al*., 1996).
- Elevated atmospheric CO_2 concentrations are known to increase the photosynthetic rate and crop yield of C_3 plants. However, it also enhances disease severity in rice and wheat (620 and 780 ppm, respectively), (Kobayashi *et al.,* 2006 and Vary *et al.,* 2015).
- C_4 plants (e.g., corn and sugarcane), however, do not profit from this enhance in atmospheric CO_2 as a result of their inherent CO_2 concentration mechanisms (Long *et al.,* 2006).
- In case of fungal pathogen *Fusarium graminearum,* enhanced CO_2 levels increased the vulnerability of wheat varieties in accordance with the virulence of the fungal isolate (Vary *et al.,* 2015). Whereas, in case of interactions between soybean and *Peronospora manshurica*, CO_2 concentrations of 550 ppm decreased the incidence of the disease by more than 50% (Eastburn *et al.,* 2010).

Impact of temperature on plant diseases

- The temperature, in general, is known to influence the amount/number of spores which are formed in a unit plant area and the number of spores delivered in a given period of time. Due to variations in temperature and moisture, environment change may modify the development rate of spores, pathogenicity of pathogens, and the resistance of the host plant (Charkraborty and Datta, 2003).

A summary of the influence of elevated CO_2 on some host crop and pathogen interaction and pathogen fitness.

Author/Reference	*Crop /Host*	*Disease/Pathogen*	*Climate Change*	*Change in Severity*
Manning and Tiedemann, 1995	Barley	Smut – *Ustilago hordei*	Elevated CO_2	Increase
Hibberd *et al.*, 1996	Barley	Powdery mildew – *Blumeria graminis*	Elevated CO_2	Decrease
Hibberd *et al.,* 1996	Barley	Barley yellow dwarf virus	Elevated CO_2	Decrease
Milus *et al.*, 2006	Wheat	Stripe rust – *Puccinia striiformis*	Elevated CO_2	Decrease
Melloy *et al.,* 2010	Wheat	Crown rot –*Fusarium pseudo-graminearum*	Elevated CO_2	Increase

(Debela and Tola, 2018)\

A summary of the influence of elevated temperature on some host and pathogen interaction and pathogen fitness.

Author/Reference	*Crop/Host*	*Disease/Pathogen*	*Climate Change*	*Change in Disease Severity*
Boland *et al.,* 2004	Wheat	Dwarf bunt- *Tilletia controversa*	Elevated temperatures	Increase
Milus *et al.,* 2006	Wheat	Wheat Stripe rust – *Puccinia striiformis*	Higher Temperature	Increase
Jesus Junior, 2007	Citrus	Anthracnose *Colletotrichum acutatum*	Elevated Temperatures	Increase
Jesus Junior, 2007	Citrus	Guignardia citricarpa,	Elevated Temperatures	Increase
Hannukkala *et al.*, 2007	Potato	Late blight – *Phytophthora infestans*	Elevated temperatures causing earlier seasons	Increase
Ghini *et al.,* 2008	Coffee	Meloidogyne incognita	Elevated temperatures	Increase

(Debela and Tola, 2018)

- Enhanced global temperature results in a variation of the spatial distribution in which a crop is vulnerable to a particular pathogen. This is true for pathogens that are in possession of specialized structures to be used under unfavorable conditions (Ritchie *et al.,* 2013).
- A particular optimum temperature is needed by both plants and pathogens to advance. Temperature is known to influence various events in a disease cycle such as germination, dispersal, survival, penetration, advancement, and also reproduction rate for various pathogens.
- High temperature and elevated CO2 concentration favor and initializes disease advancement, as well as survival and multiplication of fungal spores of various pathogens (Agrios, 2005). At increased temperatures, pathogens get activated to cause an infection. Incidence of late blight of potato and tomato, caused by Phytophthora infestans, is increased under high availability of moisture and at a temperature range lying between 7.2°C and 26.8°C. The occurrence of pathogen Phytophthora cinnamomi on Eucalyptus sp. is highly elevated when the soil temperature is between 12-30°C (Podger *et al.,* 1990).
- Sunlight influences pathogens as it leads to the hoarding up of phytoalexins in tissues of the host. Crop plants like wheat and oats are more vulnerable to rust pathogens when CO2 and temperature get elevated (Coakley *et al.,* 1999).
- For trilateral interactions, including a pathogen-relaying vector, temperature affects disease occurrence by influencing the vector. It is important for viruses, the predominantly of which are relayed by insects (Whitfield *et al.,* 2015). Also, the occurrence of viral and other vector-borne diseases also gets modified. The higher temperature in winter increases the survivability of aphids; as a result, the incidence of Barley yellow dwarf virus (BYDV) increases and also increases the incidence of viruses of potato (Thomas, 1989). For example, Banana bunchy top virus (BBTV) that is further relayed by Pentalonia nigronervosa has least death rate at 25°C with maximum expansion (Robson *et al.,* 2007) that is exactly the same temperature at which transmission of BBTV is most effective.

Impact of Moisture Availability on plant diseases:

- Moisture affects the commencement and expansion of plant diseases in many complementary ways.
- Moisture is a prerequisite factor for:
- Initiation of fungal, bacterial, nematode and certain viral pathogens.
- The development of fungal spores.
- Perforation of the host by the germ tube.
- The dispersal of pathogens either on the same plant or from one plant to another one.

With elevated temperature, high rainfall events, and enhanced atmospheric humidity occur. As a result, crops produce healthful and larger canopies which retain moisture as leaf wetness for a longer periods of time and as a result, conditions conducive for diseases such as powdery mildews and late blights occur (Coakley *et al.*, 1999). Majority of the plant diseases are facilitated by environmental conditions of rainfall, elevated air humidity and increased availability of moisture in the soil. In general, the pathogenicity of pathogens that contaminate aerial tissues is highly facilitated by rain and high atmospheric humidity. For example, the virulence of *Sclerotinia sclerotiorum* enhances as atmospheric humidity is increased, with maximum development of disease in lettuce plants as the RH crosses the mark of 80 per cent (Clarkson *et al.,* 2014).

Development of a disease can be assessed with an important factor termed as leaf wetness. For instance, virulent pathogens such as *Magnaporthe oryzae* (rice blast fungus) and *Puccinia striiformis* (stripe rust fungus) require at least 5 hours of leaf wetness for disease and symptom development (Magarey *et al.,* 2005). Moreover, the chance for dew collection and as a result, pathogen infection is elevated at enhanced temperatures. Pathogens such as *Fusarium* sp. and *Aspergillus* sp. under the influence of high humidity produce mycotoxins. For instance, under high humidity, wheat plants infected by *F. graminearum* (head blight fungus), produce mycotoxin deoxynivalenol (Beyer *et al.,* 2005 and Cowger *et al.,* 2009).

Increased water availability is favorable for foliar diseases and also for certain soil-borne pathogens such *Pythium, Phytophthora, Sclerotium rolfsii and Rhizoctonia solani.* Infection initiated by *Phytophthora capsici*, development of pathogen, and symptom development is greatest at almost 100% RH (Granke and Hausbeck, 2010). Reduced moisture in soil is known to reduce the occurrence of infection of *Ralstonia solanacearum* in tomato plants (Islam and Toyota, 2004).

Influence of Climate Change on Vector-Borne Diseases:

Both host plant and insect vector populations are influenced by environmental change and disperse the plant viruses (Jones, 2009). The likelihood of vector-borne disease in accordance to local and regional level is restricted by the environmental needs of disease vectors (Malmstrom *et al*., 2011). Phenology of the host is also affected by environmental change, thereby influencing its virus vulnerability. Global warming is known to impact the primary infection of the host, the dispersal of the infection within the host and/or the horizontal relay of the virus to new hosts by the vector. Variation in environment results in manifold effects on vectors like alteration of vector phenology, vector's over-wintering, stability, and its migration. The enhanced CO_2 concentrations have indirect influence by changing the size and composition of insects prey populations. Any variation either in host plant or insect vector population due to environment change could spread plant viruses (Canto *et al.,* 2008).

Combined effect of environmental factors:

For various fungal pathogens, the interaction of high temperatures and elevated humidity results in the development of optimum conditions for disease incidence (Clarkson *et al.,* 2014). In arabidopsis, *turnip mosaic virus* (TuMV) when exposed to heat and drought infection results in a maximum reduction in the growth of a plant as compared to each individual factor when brought into focus (Prasch and Sonnewald, 2013). In case of disease caused by *Botrytis cinerea* in grapes, relative humidity when reaches an approximation of 100% and temperature range is between 20-25°C, and these conditions are prerequisite for the development of disease (Ciliberti *et al.,* 2015).

Environmental impact on PAMP-triggered immunity (PTI)

- PTI is known to prevent proliferation of a large number of non-pathogenic microbial populations. Virulent bacterial pathogens cause the leaf apoplast to be water-soaked as part of the infection cycle (Xin *et al.,* 2016 and Schwartz *et al.,* 2017).
- Making leaves water-soaked in the apoplast under high humidity lets PTI-inducing non-pathogenic Pseudomonas bacteria to develop in host plants such as Arabidopsis, bean, and tobacco plants. PTI is a mechanism in which conserved molecules of microbes (pathogen-or microbe-associated molecular patterns, PAMP or MAMP, respectively) are recognized by plant plasma-membrane-localized pattern recognition receptors (PRR). MAM recognition causes a signaling cascade that includes protein phosphorylation, reactive oxygen species (ROS) production, Ca2+ concentration increases, and gene activation that lead to halt of microbial growth (Couto and Zipfel, 2016). Whereas under elevated humidity, stomata open while ABA accumulation decreases (Okamoto *et al.,* 2009). PTI activation triggers the closure of stomata after the recognition of MAMPs by stomatal guard cells (Panchal and Melotto, 2017), as part of the plant defense against bacterial entry into the leaf apoplast.
- Panchal *et al.,* (2016) showed that high humidity conditions blocked PTI-induced stomatal closure in both arabidopsis and bean plants. Likewise, PTI signaling can be altered by temperature changes (Vedukola *et al.,* 2019). In arabidopsis, short warm-temperature treatments (28°C for 15 minutes) induced higher PTI-associated MAPK (mitogen-activated protein kinase) phosphorylation and PTI marker gene expression after PAMP exposure, suggesting that PTI may be enhanced at warm temperatures (Cheng *et al.,* 2013).

Environmental impact on Effector-triggered immunity (ETI)

ETI is an important form of genetically controlled resistance implied against plant pathogens. During ETI, a virulence-promoting pathogen effector or its activity inside plant cells is sensed by a plant resistance (R) protein, most of which are NLR (nucleotide-binding domain and leucine-rich repeat) proteins (Jones *et al.,* 2016). This recognition triggers a signaling cascade that usually culminates in a hypersensitive response (HR), a type of programmed cell death thought to contain the pathogen at the site of infection (Mukhtar *et al.,* 2016 and Thakur *et al*., 2019). In many pathosystems, high temperatures compromise ETI. For example, the tobacco N protein for the resistance against *tobacco mosaic virus* (TMV) (Witham *et al.,* 1996), do not mount an effective ETI at temperatures higher than 30°C. The suppressive effect of high temperature on ETI is also evident in certain 'autoimmune' mutant plants in which ETI and spontaneous cell death are constitutively activated.

Concept of emerging diseases

An emerging disease is defined as an indigenous expression or group of expressions which are newly recognized or have recently appeared in an area which increases rapidly in occurrence and severity (Daszak *et al.,* 2003). It is represented by an initial development of an infection in a crop which can result in disease epidemics. The continuous evolution of emerging pathogens particularly leads to the occurrence of new, virulent strains for plants. New crop varieties are introduced in varying countries and are grown in large monoculture plots. Also, the varieties and cultivars are chosen basically on the basis of their productivity, without taking into account their vulnerability to pathogens. These facilitative conditions stand to reason why the incidence of new diseases occur and thrive (Oliver and Solomon, 2008).

Pathogen dispersion

In accordance to various countries or areas, the occurrence of emerging diseases elevates rapidly in a short period of time with greater emergence rates in certain countries than others, which might be as a result of an accumulation of favorable conditions (Daszak *et al.,* 1999). Emerging pathogens are known to have an ability to infect a large number of host plants. For example, human pathogens have been known to affect plants. *Enterobacter cloacae* is an example of a human

pathogen infecting plant hosts but is also a plant pathogen infecting onion (*Allium cepa* L.) in the USA (Bishop and Davis, 1990).

Xylella fastidiosa generally infects grape (*Vitis vinifera* L.) but is known to be the causal organism of mulberry leaf scorch in California (Hernandez-Martinez *et al.,* 2007). *Raffaelea lauricola* sp. *nov*. infects redbay (*Persea borbonia*). The fungus and its transmitting vector, *Xyleborus glabratus*, have their origin as Japan and Taiwan. The disease has also occurred in the Southeastern USA since 2003 (Rabaglia *et al*., 2006) but presently, the pathogen has been reported in Florida resulting in avocado wilt (Ploetz *et al*., 2012). *Candidatus Phytoplasma phoenicium sp. nov.* bacterium causes witches´ broom in almond with its first time report in Lebanon in the 1990s (Choueiri *et al*., 2001). Further, symptoms of almond witches´ broom were reported in Iran, along with some genetic variability among the strains (Zirak *et al.,* 2009).

Tomato leaf curl New Delhi virus (ToLCNDV) was initially reported on tomatoes in 1995 in India (Anonymous, 2016) followed by other countries in Asia. After Spain, it was reported from Tunisia in January 2015, causing a high rate of infection on cucumber and melon. *Puccinia graminis* f. sp. *tritici* is known to be available in Uganda, Kenya, Ethiopia, Sudan, Yemen, Iran, Tanzania, Eritrea, Rwanda, Egypt, South Africa, Zimbabwe, and Mozambique. It infects wheat. However, a new virulent strain was observed in wheat fields in Uganda in 1999, it was entitled Ug99. This new race surpassed the resistance provided by the gene Sr31. Relay, as in case of other rusts, is carried out by wind or by people carrying the fungus (Singh *et al.,* 2011).

Possible causes of Emerging Pathogens:

- The microbe might have been endemic in the particular crop locality but discovered on a new host recently.
- After flourishing as an endemic organism, it became pathogenic, as a result of an enhancement in its virulence, or due to increased susceptibility of host.
- The pathogen's introduction to a new locale along with unexposed hosts might be new.
- Insect vectors feed upon new plants nurturing the pathogen and relay the pathogen to other hosts.

The occurrence of diseases is an outcome of manifold factors such as interactions amongst other pathogens, host-pathogen interaction, plant-vector-pathogen interaction, and variable environmental conditions. Environmental factors could result in variation in the nature of microorganisms, converting them into opportunistic pathogens. When plants grow weak or are under stress due to climatic factors, pathogens can easily colonize hosts, thereby causing host mortality (Moricca *et al.,* 2016). Modifications in the plant-pathogen interaction process and spatial distribution are also important criterions in the incidence of emerging pathogens. Pathogens use specialized secretion systems to make infectious proteins or produce specialized structures or produce toxins to penetrate plant cells.

To respond, plants regulate defense molecules. For instance, in the interaction between avocado fruit and the fungus *Colletotrichum gloesposporioides* where the flavonoid epicatechin is modulated by the avocado fruit to protect itself from the laccase protein produced by *C. gloeosporioides*.

UV-B, O_3, and CO_2 involvement with Emergence Diseases:

Ultraviolet B (UV-B), ozone (O_3), and carbon dioxide (CO_2) are environmental factors that have been designated in accordance to environmental change and the emergence of pathogens.

Certain species show variable sensitivity to UV-B radiation; while some may be negatively influenced, others may be tolerant. Paul, (2000) suggested that elevated UV-B after inoculation lessened disease in wheat, as the influence of direct UV-B damaged the pathogen. Similarly, bacteria and fungi are generally more sensitive to damage by UV-B radiation (Caldwell *et al.,* 2007). As a result, researchers have drawn a conclusion that environment change, with enhanced solar UV-B, could expose plants to opportunistic pathogens as mentioned in the previous section.

Ozone (O_3) influences pathogens and host plants differently. Environment change has been associated neither to emerging pathogen nor to changes in plant pathogenicity gene mutations. We currently have restricted information regarding pathogen's adaptability to climate change (Desprez- Loustau *et al*., 2007).

Emergent Disease Dispersal:

As soon as new pathogens emerge, an important threat is their dispersal into new spatial distribution. The dispersal of plant pathogens takes place via momentary and long-distance dispersion pathways. Short-distance dispersal includes human practices (grafting and pruning) and vectors (e.g., insects or humans) (Ashraf *et al*., 2014).

Mitigation Strategies

Various countries are developing strategies to reduce threats by initiating regulatory measures to prevent, control, or eradicate diseases caused by potential pathogens.

Phytosanitary regulations are designed in order to prevent and eradicate pests affecting plants. For example, quarantines to prevent or delay the movement of pests from areas where they are not known to exist, also, quarantines allow delayed introduction of pathogens into new areas until risk evaluation has been carried out.

Conclusion

- There is a need to evaluate current management strategies and suggesting alternatives in order to get prepared against the challenge of environment change so as to allow the mitigation practices to be highly effective and resilient to change.
- Research needs to be carried out to study the influence of environmental change on crop as well as disease

development in accordance with varying responses of pathosystems to modified atmospheric configuration. More study is required to quantify variations in host–pathogen-environment tripartite interactions, generally for important crop species under natural environmental conditions.

- Criterions limiting the survival of pathogens need to be characterized (e.g., temperature, humidity, CO_2, O_3 and radiation).
- The risk of disease development needs to be examined to determine the spatial distribution and alteration of diseases due to environmental change.
- Plant disease development in accordance to crops needs to be modeled. Mathematical models can be used to perform quantitative evaluation and also to assess the probability of introduction, proliferation, and dispersion of diseases, and the immensity of their influence on crop's productivity under varying environmental conditions.
- Participation of national and international organizations to provide free information to be dispersed among scientists, governments, and the public would be crucial to minimize the threat of emergent pathogens.

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