

# Interkingdom Three-Way Synergy Modulating Adaptation and Secondary Metabolites

Vikrant Arya<sup>1,\*</sup>, Ranjeet Kaur Parmar<sup>2</sup>

<sup>1</sup>Department of Pharmaceutical Sciences, Government Pharmacy College Rakkar, Kangra, Himachal Pradesh, INDIA.

<sup>2</sup>Department of Pharmaceutical Sciences, Government Pharmacy College Kangra at Nagrota Bagwan, Himachal Pradesh, INDIA.

## ABSTRACT

Mutualistic complexities in nature represent an inherent part of adaptation. Interkingdom interactions among organisms helped them to survive against biotic and abiotic stress. Although mutualistic associations have been commonly observed among plants-fungi and plant-virus but the concept of tripartite association involving plants-fungus-virus has not been explored so far. The literature review depicted the presence of interactions between plants and the fungus, in which fungal endophytes/AMF aid in plant adaptation. In the case of plant-virus interactions, several viruses aid in modulating the secondary metabolites. The associated mutualistic interactions among organisms complement their survival in nature.

**Keywords:** Mutualistic associations, Secondary metabolites, Symbiosis, Three-way symbiosis.

## Correspondence:

**Vikrant Arya**

Department of Pharmaceutical Sciences,  
Government Pharmacy College Rakkar,  
Kangra-177043, Himachal Pradesh, INDIA.  
Email: arya.vikrant30@gmail.com  
ORCID: 0000-0002-6808-1754

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## INTRODUCTION

Biotic and abiotic stress triggers specialized mechanisms in plants, enabling them to interact with their surroundings.<sup>[1]</sup> These interactions facilitate organisms to survive under the most stressful conditions on Earth.<sup>[2]</sup> Symbiosis emerged as an outcome of these inter- and intra-kingdom associations, thereby enabling organisms survival.<sup>[3]</sup> The mutualistic relationships among different kingdoms result in the development of survival instincts along the evolutionary path of organisms.<sup>[4]</sup> Plant symbiotic associations majorly encompass mutualism (lichens, mycorrhizae), parasitism, and commensalism.<sup>[5]</sup> Mutualism, as explained by Pierre-Joseph Van Beneden, a Belgian zoologist, includes the beneficial attributes of interacting species.<sup>[6]</sup> This survival instinct has been recorded among several organisms belonging to different kingdoms.<sup>[7]</sup> Mutualistic partners acquired the advantage of resource acquisition, which includes shelter, food availability, and enhanced survival tactics from predators.<sup>[8]</sup> Plant-focused mutualistic relationships typically include myrmecophytes (plant-insect mutualism) and mycorrhizae (plant-microorganism mutualism).<sup>[9,10]</sup> In a classical example of the acacia tree and ant (*Pseudomyrmex ferrugineus*), a mutualistic association has been observed in which ants protect the acacia tree from herbivores and, in return, the tree provides shelter (domatia)

and a food source (nectar) to ants.<sup>[11]</sup> Although two-way symbiosis has been established to understand the intricate association among different kingdoms, research revealed the significance of the third partner involved in mutualism, which opens a new avenue of discussion among researchers of associated fields. A study by Defosse *et al.*, 2009 highlighted the significance of tripartite association among myrmecophytes, ants, and fungi.<sup>[12]</sup>

## METHODOLOGY

A comprehensive review of existing research was performed, searching prominent scientific databases such as Google Scholar, PubMed, and Web of Science. This extensive search involved the use of various keywords directly related to the topic, viz., 'symbiosis', 'tripartite mutualism', 'plant-fungus-virus association', and 'three-way symbiosis'.

## Plant-Fungus And Plant-Virus Interactions

The two-way symbiosis involving plant-fungus and plant-virus revealed its role in the modulation of secondary metabolites as well as in adaptation. In a study by Srivastava *et al.*, (2017), the host plant (*Papaver somniferum*) is associated with begomovirus (*Ageratum enation*). The modulation of secondary metabolites has been observed in virus-infected plants, resulting in a reduction in the production of morphine, thebaine, codeine, and papaverine, and, on the contrary, the biosynthesis of noscapine increased drastically, indicating modulation of secondary metabolites.<sup>[13]</sup> Zaim *et al.*, (2014) also confirmed the favourable effect on the production of morphine and codeine on exposure to Poppy mosaic virus.<sup>[14]</sup> In another study, the same plant, *P. somniferum*, is mutually associated with fungal endophytes, facilitating the modulation of biosynthesis of benzyloisoquinoline-type



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alkaloids.<sup>[15]</sup> It is evidenced from the research that viral and fungal endophyte prevalence in *P. somniferum* modulates the synthesis of alkaloids.<sup>[14,15]</sup>

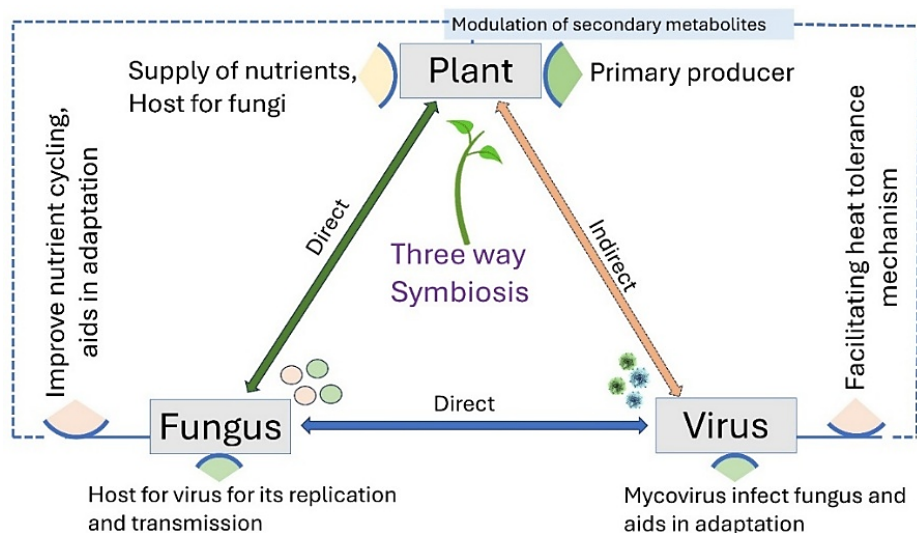
In a study by Gachon *et al.*, (2004), TMV-induced overexpression of scopoletin and scopolin was observed in *Nicotiana tabacum*.<sup>[16]</sup> Furthermore, in another study, it was evidenced that root colonization by AMF (arbuscular mycorrhizal fungi) resulted in biomass production and volatile oil accumulation.<sup>[17]</sup> *N. tobacum*

exhibited a response to viral exposure and fungal acquisition, which was reflected in its metabolic profile.<sup>[16,17]</sup>

Zhang *et al.*, (2022) reported that in *Cucumis sativus*, viral infection (cucurbit chlorotic yellows virus) typically depresses pathways for defence mediators (flavonoid, terpenoids) while upregulating metabolism of lipid, amino-acid and nucleotide.<sup>[18]</sup> The roots of the plant (*C. sativa*) have also been associated with AMF for plant growth by facilitating nutrient reuptake.<sup>[19]</sup>

**Table 1: Symbiosis-mediated adaptation in plants.**

Host plant	Plant-virus interactions			Plant-fungus interactions		
	Associated virus	Virus-plant Symbiosis impact on secondary metabolites	Reference	Associated fungi with the host plant	Fungus-plant symbiosis outcome	Reference
<i>Papaver somniferum</i> , Papaveraceae	<i>Ageratum enation</i> virus	Significant reduction in the production of opioid alkaloids (morphine, thebaine, codeine, and papaverine) and an increase in the biosynthesis of noscapine (non-narcotic alkaloid)	[13]	Endophytes	Biosynthesis modulation of benzyl-isoquinoline alkaloids	[15]
	Poppy mosaic virus	Favourable effect on the production of morphine and codeine	[14]			
<i>Nicotiana tabacum</i> , Solanaceae	Tobacco mosaic virus	Over-expression of the enzyme (scopoletin glucosyltransferase)	[16]	AMF	The root colonisation by the fungus significantly increased biomass production and essential oil accumulation	[17]
<i>Cucumis sativus</i> , Cucurbitaceae	Cucurbit chlorotic yellows virus	Viral infection represses the metabolism of secondary metabolites (flavonoids, terpenoids)	[18]	AMF	Improves plant growth, nutrient reuptake, and photosynthesis	[19]
<i>Datura stramonium</i> , Solanaceae	Pepper mild mottle virus, Tomato mosaic virus, and Tobacco mosaic virus	Increase in hyoscyamine content	[20]	AMF	Aids in plant adaptation	[21]
<i>Carica papaya</i> , Caricaceae	Babaco mosaic virus	Increase in phenolic and flavonoid levels	[22]	AMF	Strong growth response observed in the plant	[23]
<i>Zea mays</i> , Poaceae	Sugarcane mosaic virus	Accumulation of the salicylic acid	[24]	AMF	Increases crop productivity	[25]
<i>Solanum lycopersicum</i> , Solanaceae	Potato spindle tuberoiroid	Increase in phenolics	[26]	AMF	Regulate root development	[27]



**Figure 1:** Symbiosis-mediated modulation of secondary metabolites.

It is evidenced from the results of Mihalik *et al.*, (2022) that there is a positive effect on the biosynthesis of hyoscyamine when the plant is infected with a specific type of virus (Tomato mosaic virus and Tobacco mosaic virus).<sup>[20]</sup> The same plant has also been associated with AMF, which aids in its adaptation.<sup>[21]</sup> In two different studies involving *Carica papaya* mutualism, one reported a potyvirus-induced increase in secondary metabolites (phenolics and flavonoids),<sup>[22]</sup> while the other reported predominance of AMF in roots of *C. papaya* responsible for its growth.<sup>[23]</sup>

A study on virus (sugarcane mosaic virus) infected *Zea mays* reported the significant accumulation of salicylic acid (defence signal),<sup>[24]</sup> and another study confirms its association with AMF for productivity enhancement.<sup>[25]</sup> An increase in the phenolic content was observed in virus-infected *Solanum lycopersicum*,<sup>[26]</sup> and in another study, the same plant was also found to be associated with AMF required for its optimum growth and development.<sup>[27]</sup> The associated interactions among plant-virus<sup>[28]</sup> and plant-fungi have been represented in Table 1. The literature revealed that the tripartite association involving plant, fungus, and virus has not been much explored so far.

In a study by Marquez *et al.*, (2007), a tripartite association has been observed in tropical panic grass, virus and fungus. The fungus (*Curvularia protuberata*) present in the host grass encompasses a dsRNA virus, which enables it to survive under excessive heat. The existence of a mycovirus in a fungal endophyte enables it to adapt against thermal stress, and in return virus sustains its survival in the respective host.<sup>[29]</sup> Based on the discussion mentioned above, the proposed tripartite association involving plant-fungus-virus has been represented in Figure 1, which predicted a direct mutualistic interaction among plant-fungus and fungus-virus, whereas an indirect association has been observed between plant and virus.

## CONCLUSION

Mutualistic relationships served as an important marker for organisms surviving in extremes of nature. The two-way mutualistic association has been commonly observed among plant-fungi, plant-viruses. Modulation of secondary metabolites was also observed in these two-way mutualistic associations, but the complexities of the tripartite association have not been explored so far. The information incorporated in this communication will serve as a conceptual framework to study more insights about the tripartite association involving plant-fungus-virus.

## ABBREVIATIONS

**AMF:** Arbuscular mycorrhizal fungi; **TMV:** Tobacco mosaic virus; **dsRNA:** double-stranded RNA.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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