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Pests of Mushroom and their Ecological Management Strategies: A Review

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ABSTRACT: In the recent years, mushroom production is gaining popularity in most part of the world as the enterprising assists to transform the agricultural wastes into high healthy nutritional foods. Infestation by several pests poses serious threats to mushroom crop during its cultivation. The major pests that are associated with mushroom crops are arachnids, insects, and nematodes. The main challenges in the pest management of mushrooms are inadequate scientific researches for the management of pests, use of less innovative technologies with inadequate information for the control of pests, lack of effective formulations in management packages and, lack of thorough analysis of the mushrooms ecosystem in its appropriate environmental, social and ecological settings. Despite of that Integrated Pest Management (IPM) is considered as the most effective and efficient pest management tool which includes cultural, biological, physical, mechanical and chemical methods, therefore, IPM assists to furnish the mushroom cultivation with natural and environment friendly tools to manage mushroom pests, which assist to mushroom growers to produce healthy and nutritious mushrooms in their farm, thus, accomplishes their better noteworthy financial viability.

Keywords: Mushroom, Ecosystem, Cultivation, Pests, Integrated Pest Management etc.

INTRODUCTION

In the present context, cultivation of mushrooms is becoming popular across the globe as an edible fungus. Mushrooms are considered as important crop like field and horticultural crops that can be eaten either fresh or after processed, particularly canned. Throughout the world, more than a dozen of edible fungi species are grown. Among them, *Agaricus bisporus* (white button mushroom) accounts for around 70 per cent of all mushroom production, growing in more than 100 nations (Chang and Miles, 1989). China became the leading producer of mushroom in the world, which alone accounts for more than 30 percent (Fletcher and Gaze, 2007). Mushroom cultivation has relationship with the transformation of agrarian and agro-industrial waste into food of high healthy nutritional benefits and has great economic importance in our society, which is considered as a naturally feasible alternative (Pontes *et al.,* 2018). The metabolic potential of mushroom growths happens through degradative microbiological activities (Fig. 1), which to accomplish their better noteworthy financial viability in which optimal synthetic, physical, natural and mechanical or technological process should be controlled (Cunha Zied *et al.,* 2020).

In mushroom cultivation, infestation by different types of pests creates serious threats to the mushrooms during its cultivation process. Mushrooms are more prone to several types of insect pests that tend to cause significant crop loss (Jenita *et al.,* 2021). Therefore, it becomes essential to control several pests for the optimum yield of mushrooms in farm.

It is pertinent to mentioned that adoption of Integrated Pest Management (IPM) technique becomes more effective and efficient to control pests in mushroom. Essentially, an IPM program distinguishes and screens the pests, exploits the alternatives that deal with the vermin through cultural methods and synthetic pesticides when required (Fleischer, 2002).

In IPM, biological method for pest control considered as the most effective for the management of different type of pests, therefore, acts as a significant tool for the ecological pest management strategy in mushroom cultivation (Keil and White, 2004). For instance, natural anti-pest abilities of wasps, bacteria, and/or nematodes are used to control mushrooms associated pests. Therefore, biotic control furnishes the mushroom cultivator with natural tools to manage mushroom pests (Rinker, 2002).

Infestation by Pests and Pathogens at Different Phases of Mushroom Cultivation

During the growing stages of mushrooms, there are some critical vulnerability stages at which mushroom become more susceptible to attack by several pests and pathogens. The following images (Fig. 2 and Fig. 3) present the critical stages during mushroom production at which several pests and pathogens attacks on mushrooms (Fletcher and Gaze, 2007).

Distinct Phases During Mushroom Cultivation

Phase 1

After the wetting and mixing of raw materials, the composting takes place into the long narrow stacks.

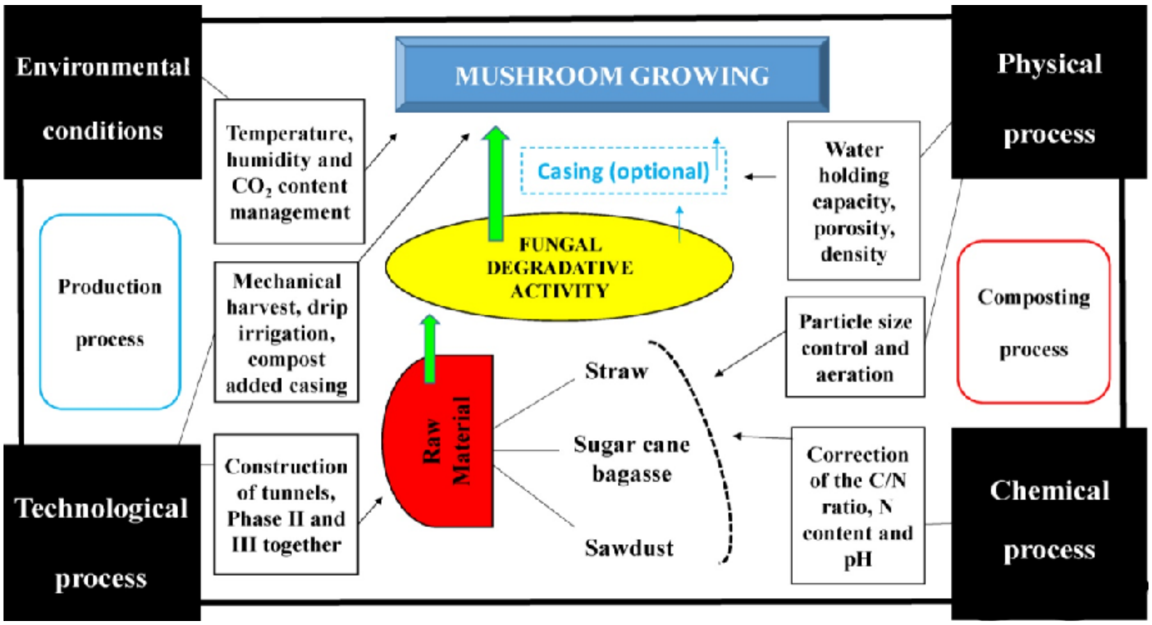


Fig. 1. Schemes for mushroom development and the principle physical, synthetic (chemical), natural (environmental), and technological process/conditions that can impact the important phases during the production process of mushrooms (CunhaZied *et al.,* 2020).

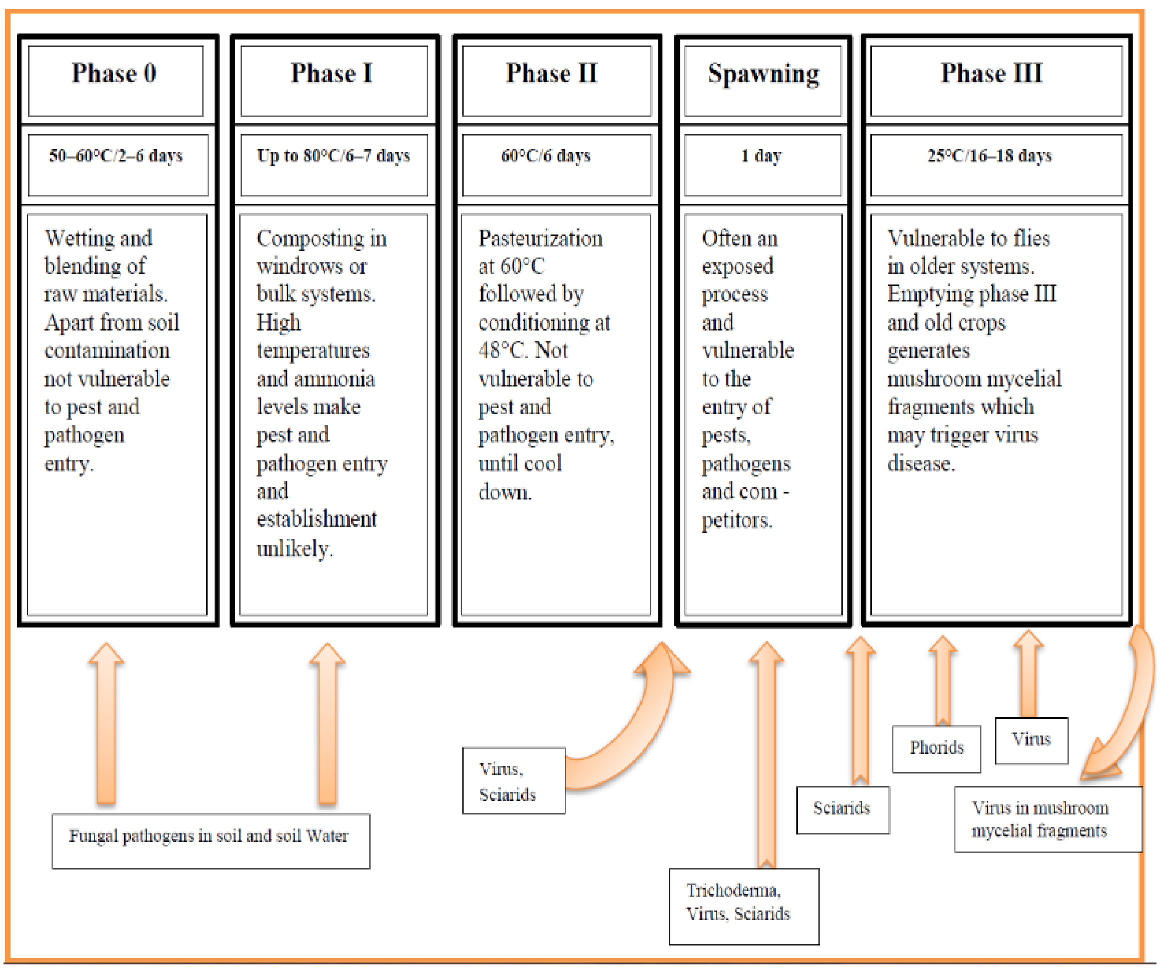


Fig. 2. Critical stages during the mushroom production cycle, which are more susceptible for the entry and establishment of pests and pathogens.

This process takes 7 days to complete. The temperature of the compost stack must be in between 70-75°C; high temperature is required to kill pest and pathogen which is present in manure. The materials are turned by mechanical compost turners for several times. Large quantity of water is used for compost production. The water must contain large amount of organic materials which are fermented under hot water. The water also contains soluble salts which is essential for the composting or mushroom mycelium growth (Fletcher and Gaze, 2007). This phase will lasts from 6 to 14 days, but it depends on the nature of substrate materials used at the beginning of the process and their characteristics at each turns (Beyer, 2016).

Phase 2

The composting process is continued until it become suitable for the growth of mushroom. Pasteurization of substrate is essential during this phase to kill the harmful living organisms present in the compost. During this time, compost either filled in the growing container or it can be processed in the bulk (Fletcher and Gaze, 2007).

Spawning, Spawn-Running and Phase-3 Compost

Spawning

Once completed the phase 2 process, it needs to cool at ±25°C and it will be ready for Spawning. At this stage the concentration of ammonia level in the compost should be below 5 ppm. Next, spawn and sterilized grains are mixed into the compost by mechanical means.

Spawn-running

Spawn running is colonization of compost from grain inoculum; it takes about 13-18 days. The environmental condition also required for successful spawn run. High relative humidity and temperature of 25 degree is essential to prevent the compost from drying. Spawn running process may takes place in the final growing container or in the bulk.

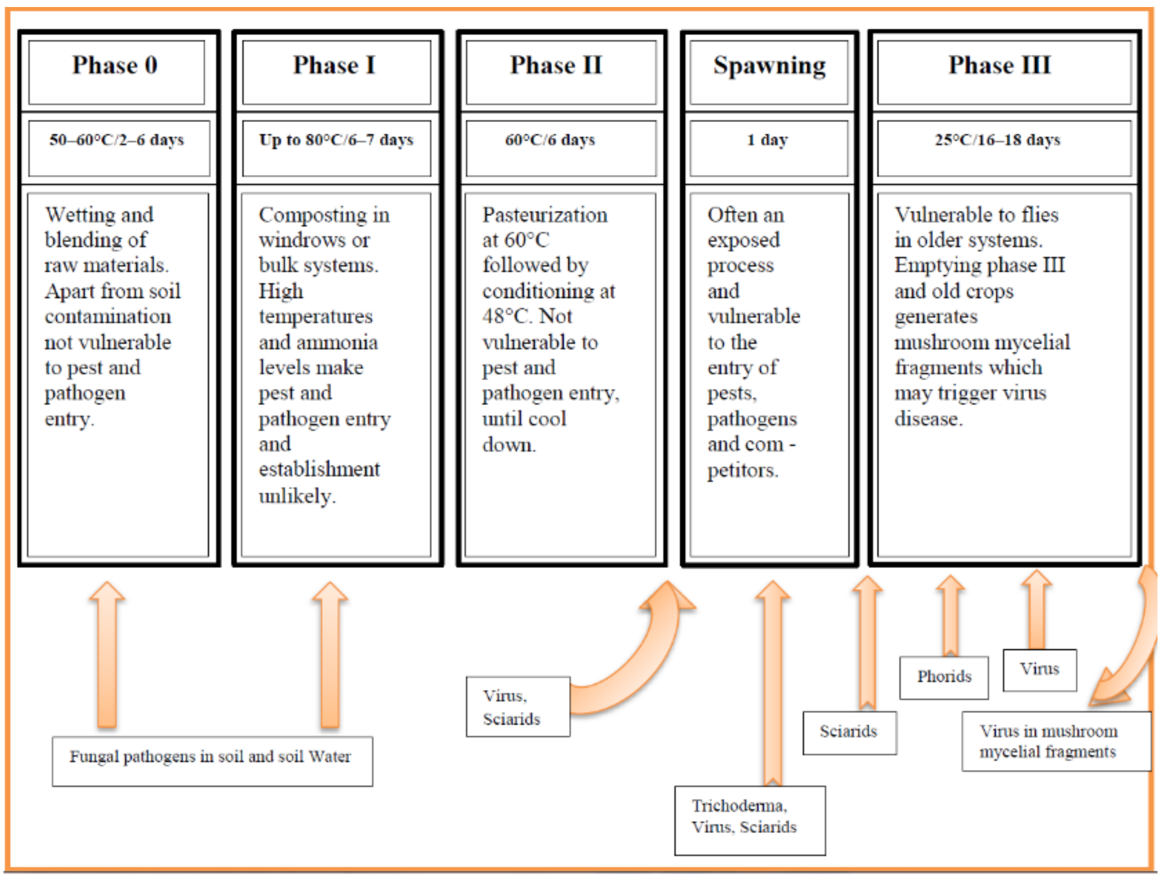


Fig. 3. Relation between the critical stages during mushroom production, and the entry and establishment of pests and pathogens.

Phase 3 compost

This process is used to transform fully colonized compost into bulk. Controlling oxygen levels during bulk spawn running process is very important; oxygen level should not fall below 16% (Fletcher and Gaze, 2007).

Economic Threshold Level (ETL) and Economic Injury Level (EIL) of Insect Pests

The concept of Economic Injury Level (EIL) and Economic Threshold Level (ETL) is displayed in Fig. 4. EIL is the lowest population density of pests, which will cause economic losses. Actually, it is a theoretical value at which pest management decisions need to apply before pests reaching the economic injury level, otherwise results in economic damage. When pest will reach the EIL, the cost of losses equals to the cost of management practices. So, it is advised to adopt different management strategies before reaching the pests to the EIL. On the other hand, ETL is the minimum pest population density at which effective control measures should be taken to prevent the pests population against reaching towards the economic injury level (Tang *et al.,* 2012). Therefore, ETL is considered as the appropriate stage to adopt the best pests management strategies.

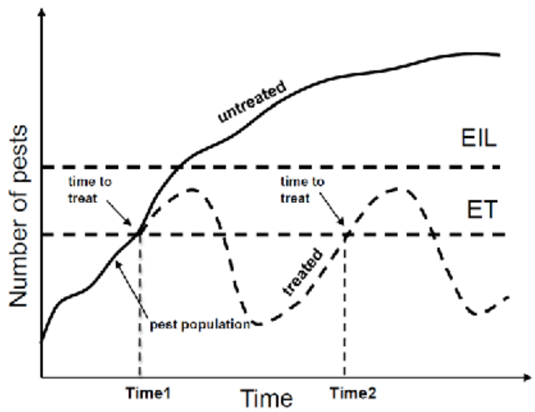


Fig. 4. ETL and EIL. The arrows indicate points when pest levels exceed the economic threshold and an IPM strategy would be applied. The graph demonstrates that the pest population is changing over different period time. Arrows in the figure depicts the points when pest levels exceed the ET (Economic Threshold) and IPM strategy needs to be applying to prevent from economic damage (Source: Tang *et al.,* 2012).

Different Pests Affecting the Mushroom Production

FLY

Flies are considered as the serous insect pests of mushroom, which infest different types of mushrooms throughout the world. Fly maggots' outbreak mostly seen especially in the next year of mushroom cultivation. Generally, maggots live in foul rotting objects especially in the ammonia smell from the packs of mushroom. The damaging symptoms include the changing of mushroom packs to brown or black and also sometimes found bacterial spots on the bags (Thongnaitham, 2012). The major flies that are probably found in the mushroom houses are described below.

(i) Sciarid Fly. Throughout the world, Sciarid fly **(***Lycoriella mali)* considered as one of the most important insect pests of mushroom crop, which leads to significant economic damages in different types of mushrooms (Binns, 1981; Lewandowski *et al.,* 2004). These flies are black in colour and small in size, which size is about 1⁄4 inch (3–5 mm) long with long antennae and grey wings (Fig. 5). Females are larger and abundant compared to males (Keil, 2002). The most common sciarids that are found in mushroom houses are *Lycoriella auripila*, *Lycoriella mali* and *Lycoriella solani*. All these three species of sciarids, mostly infect on the composts of mushroom, particularly when the compost starts to cooling from peak heating and spawning time. Female enters inside the mushroom growing rooms and lay more than 100 eggs in the compost. Further, the larva hatches within 3 to 5 days and starts to feed on the developing mycelium and compost, therefore, prevents the mycelial growth, as well as alters the physical and chemical structures of compost that makes the substrate unsuitable for the crop growth (Keil and White, 2004).

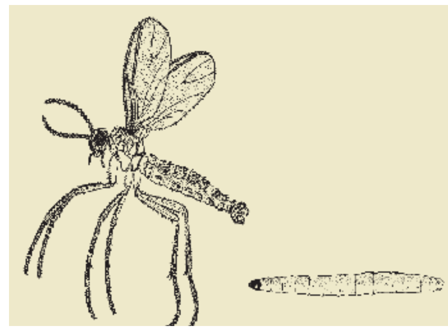


Fig. 5. Sciarid fly and larvae (Source: Keil, 2002).

(ii) Phoridae (Phorid) Fly. Phorid flies are small in size and have very small antennae (Fig. 6). These flies are found either winged or wingless. Females are mostly like to lay eggs in the mushroom compost. Phorid fly, especially *Megaselia halterata* make direct damage on crops by direct feeding on mushroom, and indirectly by the transmission of fungal pathogens.

Fig. 6. Phorid fly and larvae (Source: Keil, 2002).

During the larval period of insect, they will destroy the fibres of mushroom and frequently pierced the roots and caps of mushroom. However, Phorids caused less damage than the sciarids (Keil, 2002; Thongnaitham *et al.,* 2012).

(iii) Cecidomyiidae (Cecid) Fly. Among different species of flies, the Cecids are the most potentially damaging flies in mushrooms **(Fig. 7).** Generally, three species of Cecid are found in mushroom houses, namely *Mycophilaspeyeri, Mycophilabarnesi* and *Heteropezapygmaea*. These Cecids are occasionally seen as grown-up flies because mother larva more often directly give birth 10 to 30 daughter offspring. These flies are usually enters in to the pupal stage and becomes adults, which must mate prior to laying eggs.

Therefore, multiplication achieved without mating, which gives daughter larva directly. This form of reproduction termed as "Paedogenic Parthenogenesis" (Keil, 2002). These three species can cause huge economic damage by feeding on mycelium, gills and stipe of the mushroom.

Fig. 7. Cecid fly and larvae (Image Source: Keil, 2002).

(iv) Fruit (Pomace) Fly. These flies are minute and black in colour and are similar to fruit flies in appearance (Fig. 8). Generally, these flies are commonly found in damp places. In mushroom, significant damaged caused by the larva, which will pierce the basal portion of mushroom, especially during the development period of mushroom, resulting in atrophid mushroom size. On the later stages, mushroom will turns to black in colour and finally rotting will takes place throughout the whole pack. Whereas, severe outbreak of the pest generally noticed after 4 to 5 months after mushroom cultivation (Thongnaitham *et al.,* 2012).

Fig. 8. External morphology of mushroom fruit fly (Source: Thomas, 2017).

MITES

It is pertinent to mentioned that mites are commonly found in unhygienic mushroom houses. Well pasteurized compost has low proportional of mites' infestation. The most common and important mites that are found in mushroom houses are *Tarsonemus myceliophagus, Pygmephorus* spp. and *Tyrophagus* spp. (Dhooria, 2016). Generally, mushroom mites enter in the mushroom houses through raw materials. Mites are mostly found in straw, hay, grains and other materials that are used for the cultivation of mushroom.

Specifically, these mites mostly feed on the mycelium of mushroom, as well as on the mature and immature mushrooms. Despite, several species of mites are also used as a bio-control agent to control nematodes and other harmful mites by feeding on them (Singh and Sharma, 2016). By the supporting evidence, it was mentioned that mites will cause economic loss from 20 to 80 per cent in on-harvested mushrooms (Jompong *et al.,* 2015).

i). Tarsonemidmites: These mites are very small in size and pale brown in colour that can only visible under microscope (Fig. 9). Tarsonemid mites have short lifecycle, which completed one generation within 8-12 days. Fertility of female mites is relatively slow, which lays around 20-30 eggs. The typical damaging symptoms of Tarsonemid mites are spore carriers, which turns colour of mycelium from brown to dark and loosening of mycelial membranes in the compost (Hussey and Gurney, 1967). Mainly damage is caused by feeding on the hypha and mycelium of mushroom, as well as on the mycelium of other harmful competing fungi that are present in the compost of mushroom. The initial damaging symptom shows the reddish brown discoloration at the base of the stem of mushrooms. At severity, mushrooms will detach from the growing surface (Singh and Sharma, 2016).

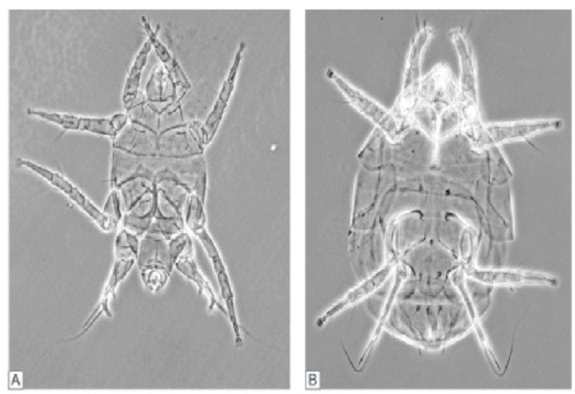


Fig. 9. *Polyphagotarsonemus latus*: A: Male, B: Female (Source: Labanowski and Soika, 2006).

ii). Red pepper mites/ Pygmy mite: The colour of the mite is yellowish-brown to reddish brown and has flattened looks. On the other hand, these mites having high fecundity rate, therefore capable to multiplicate in a rapid rate.

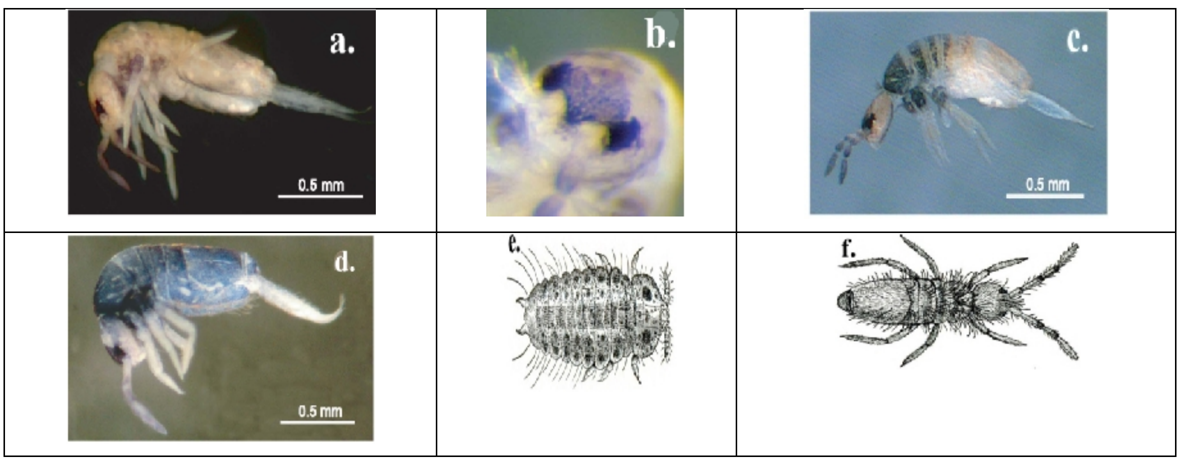
These mites are usually related to *Penicillium* and *Trichoderma* molds, upon which they feed. These pests are secondary pests of mushroom that assist to indicate the presence of *Trichoderma* (green mould) in the mushroom compost. Basically, they do not feed on mushrooms, but makes the mushrooms unsaleable. Mites damage the mushrooms by spreading the spores of *Trichoderma* between the bags; therefore spread the disease infestation on the other compost too (Singh and Sharma, 2016).

Fig. 10. Red pepper mites on the mushrooms surface (Source: Rinker, 2017).

iii). Springtails: These insects are very small (1-2mm) in size, wingless and grey, black, or brown in colour. Female lays their eggs on the moist paddy straw, compost and buttons of the mushrooms. Surprisingly, these mites are active throughout the year and usually feed on algae, fungi, dead animals, and dead and decaying vegetable matters (Davis, 1938; Singh and Sharma, 2016; Ahmed *et al.*, 2018). It mainly damages the mycelium and sporophores in the compost of both oyster and button mushroom. Besides, it also feeds on fruiting bodies and gills of mushrooms (Singh and Sharma, 2016). To control, fumigation of Ethyl Formate assist to prevents the invading of springtail mites and other insects in the mushroom houses (Ahmed *et al.,* 2018).

NEMATODES

Plant parasitic nematodes are also known as Roundworms or eelworms, which are very small in size. Typically, nematodes size ranges from 0.2mm to 6 mm in length (Coles, 2002). Nematodes are also considered as the major pests of mushroom crops and have two different habits. They may be either Saprophagous, which mainly feeds on dead and decayed organic materials or Mycophagous, which intensely feeding on fungus (Keil and White, 2004). Mainly, parasitic and saprophytic nematodes damage the mushroom crops. It was mentioned that the plant parasitic nematodes feeds upon the mushroom's mycelium directly.



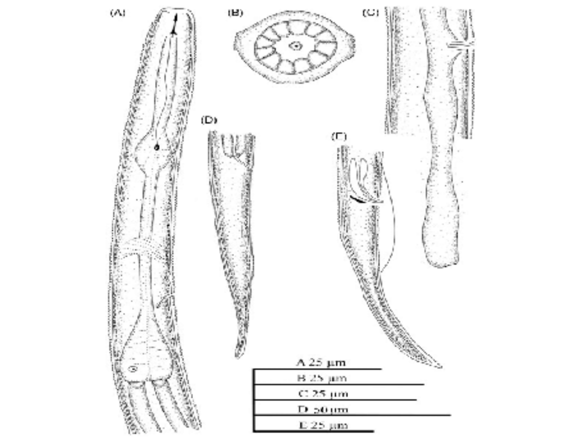
a. *Lepidocyrtus lanuginosus habitus*; b. *Lepidocyrtus lanuginosus* dorsal head; c. *Lepidocyrtus bicolour i ssp. nov*. *habitus;* d. *Lepidocyrtus cyaneus habitus.* e. *Achorutesarmatus* f. *Lepidocyrtus lanuginosus*

Fig. 11. External morphology of different species of springtails (Image Source: Davis, 1938; and Mateos, 2012).

These types of nematodes are commonly known as Mycophytic nematodes or fungal feeding nematodes. The most commonly found mycophagous nematodes in mushrooms are *Ditylenchus myceliophagus* and *Aphelenchoides composticola* (Coles, 2002; Rinker, 2017).The infestation of nematodes is severe when the compost environments become rich in water, oxygen, and foods. Sufficient level of these elements act as an excellent source of food and habitat for the growth and development of nematodes. Usually, the infestation of nematodes becomes severe when compost has not been pasteurized properly (Coles, 2002; Ahlawat and Tewari, 2007).

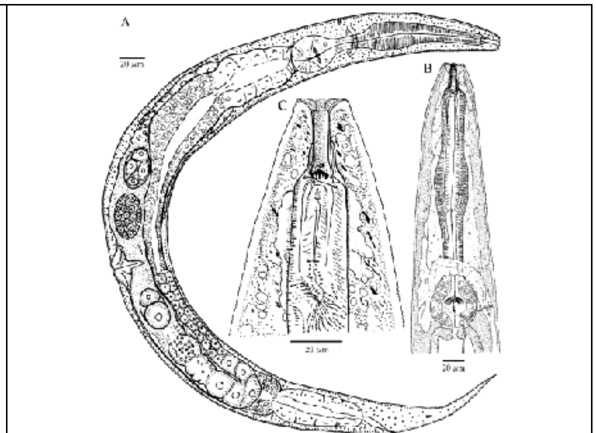
Mycophagous nematodes uses tylet to damage the crops by piercing the mycelium and feed upon the mushroom mycelium, and finally destroying the crops. The damaging symptoms of Mycophagous nematodes lead to disappearance of the spawn, destroying the mycelium and rotting of the compost. At severity, compost becomes soggier and also emits sour smells from the casing (Coles, 2002; Rinker, 2017).

Saprophytic nematodes are free-living nematodes that have chewing type of mouth, which ingest bacteria, fungal spores and protozoa, but never attack on mycelium.The most commonly found saprophytic nematodes of greatest concern to mushroom growers in mushroom house are *Acrobeloides aplíticus,* *Acrobeloides buetschii, Caenorhabditis elegans, Cruzenemalambdiensis, Panagrellus redivivus* and *Rhabditis* spp. The damaging symptoms of the saprophytic nematodes lead to disappearance of the spawn and rotting of compost/casing takes place and turns the compost into a brown to black soggy mass (Wuest and Bengtson, 1982; Coles, 2002).



A: Anterior end; **B:** cross-section of midbody; **C:** post-vulval uterine sac; **D:** Female posterior end; **E:** Male posterior end

Fig. 12. *Ditylenchus myceliophagus.* Image Source: (Goodey, 1958).



A: Entire body; **B:** Stoma and pharynx, lateral view; **C:** Stoma, ventral view.

Fig. 13. *Rhabditisrainain. sp. Hermaphrodite.* (Source: Osbrink and Carta, 2005).

At lower saprophytic level, there may be little effects on the growth of the mycelium, whereas, at higher infestation, mycelium growth rates become weak and slow. Due to this, mycelial strands become completely degraded on the later stages. Furthermore, number of researches had proved that saprophytic nematodes made severe damages on the compost. Therefore, lowers the quality and quantity of fresh mushrooms. It has also negative effects on the whiteness of mushrooms (Grewal, 1991; Coles, 2002; Rinker, 2017).

Integrated Pest Management (IPM) in Mushroom Farming

IPM is an ecological approach, which integrates the biological, cultural, mechanical, physical and chemical measures to control different pests based upon sound ecological principles and knowledge. The four main principles/components of IPM are Sanitation, Exclusion, Monitoring and Pest Control (Sandler, 2010; Shamshad, 2010). An IPM assists to manipulate the growth and development environment of pests that helps to avoid the pests attack in the mushrooms, and becoming the most effective, popular and successful tool for the pest control. Furthermore, it also encourages the mushrooms growers for the limited reliance on synthetic pesticides. These highlights make the IPM approach acts as the best and prudent methods for the long-term sustainable pests control (Coles, 2002). Therefore, an appropriate IPM strategy is crucial for the lowering of detrimental effects caused by the mushroom flies and other pests (Rinker and Bloom, 1982; Rinker, 2017).

Cultural Practices. It is one of the popular components of the IPM, which includes any modification during crop production that results in lowered the pest population below the ETL. Cultural method for pests control considered as the purposeful manipulation of crops production practices, which lowers the pest population and protect the crops against heavy economic loss or damage (Schellhorn *et al.,* 2000).

(i) Shortening the crop cycle

Shortening of cropping cycle is an economic management practices to control fly and disease problem. At the end of phase 2, rapid cool down will reduce the time available for fly invasion. Less fly problem will be seen if the spawn run is short (Rinker, 2017).

(ii) Prevention

Preventive practices are most effective way to control several pests in mushroom house. Cracks in walls, pipes, doors and around the air conditioners are the routes of initial fly invasion. Therefore, installation of fine wire gauge or fly nettings over the all windows, doors, ventilators, and openings during and after spawn run is essential against the entry of insect pests, mites and foreign particles. If the flies can be removed during the time of casing, they will have little or no direct impacts on mushroom (Popenoe, 1917; Rinker, 2017).

(iii) Sanitation/Hygienic Measures

Good sanitation practices are important for fly control. Flies can breed in spent compost, which may serve as breeding material. So, spent compost needs to be removed from growing area. It is highly recommended to make inside, outside and surroundings of the production unit should be cleaned (Bruno *et al.,* 2013; Rinker, 2017). High-tech facilities are mostly used in the production unit to disinfect the room after the crop cycle, known as "Cooking-Out", in which steam vapour at 70 °Care used for 12 hours (Fletcher and Gaze, 2007). This treatment is used to eliminate several mushroom pests and diseases. For complete destruction of nematodes in handling tools, it needs to heat for 1-2 min in boiling water. Similarly, mushroom cultivation rooms can also be disinfected by using 10% Clorox solution or 70% ethyl alcoholor 2 % formalin (Nieuwenhuijzen and Oei, 2005).

(iv) Pest exclusion during cropping

This principle depicts the prevention of entry of several pest organisms from old to new mushroom house or rooms, where it will create damage to the crop and prevents escaping from older ones. Continuous monitoring of pests is required to know about presence or absence of harmful insect pests nearby mushroom house. To exclude pests' infestation in mushroom, care needs to be taken especially during the time of spawn run and when spawn is running in the compost (Staunton and Dunne, 2001).

There are numerous ways to achieve exclusion; the structural integrity of mushroom house needs to maintain by sealing the walls, holes and cracks present in the mushroom house with urethane insulation. Similarly, filter the air before entering into the mushroom house, secure the openings (windows, doors, ventilator openings, exhaust fan openings, drainage holes) of rooms with fine mesh wire, clean and/or sanitize the equipment or tools before entering into the room and use filter or fly nettings to seal doors. In spite, buildings materials are also important because wood provides good hiding place for several pests and pathogens because wood is organic and porous in nature (Coles, 2002).

(v) Pest monitoring

Continually monitor the crops against pest attack, determine the pest problems and appropriate treatments against several pests (Staunton *et al.,*1999). Keep monitoring on adult fly number, which will give the information about what kind of pest are present and whether their numbers are increasing or decreasing. Various devices are used to monitor the flies, such as different colored sticky traps and different light bulbs. For instance, Insectocuter is a modern device, which is commonly used to attract and kill the flying insects in mushroom house. In addition, black light traps or UV lights are also used to control several insect pests. These lights are effective for those insect pests that are mainly active and flying during the night time (Staunton and Dunne,2001).

Biological Control. Biological control means the controlling of different types of pests such as flies, mites, nematodes, and other harmful organisms by releasing biological control agents in the crop environment. This method requires controlling agents, such as parasites, parasitoids, predators and pathogens to check the pest population under certain boundaries (Flint and Dreistadt, 1998).

(i) Use of Bacteria to control pest

Bacillus thuringiensis is a gram positive bacterium, which has been using mostly in farming sector as biological pesticide to control several insect pests. Bt toxin requires alkaline environment for its activation. Therefore, *Bacillus thuringiensis* subspecies *israelensis* (*Bti*) has no toxic effects on mammals because pH of mammalian stomach is acidic in nature. However, it becomes more toxic against insect because pH of insects stomach is alkaline in nature. It has good control against dipteran insect larvae with optimal toxicity for *Lycoriella mali* and *Megaselia halterata*. According to Keil (1991), *L. mali* and *M. halterata* in a commercial trial was significantly controlled by the formulation of *Bti*. It was advocated that *Bti* can also toxic against black flies, immature mosquitoes and dark-winged fungus gnats. Therefore, the application of *Bti* in compost and casing material assist to increase the yield of mushroom and keep the mushroom free from pests (Goldberg and Margalit 1977; Undeen and Nagel, 1978; Osborne *et al.,* 1985).

(ii) Predatory Mites

It was reported that predatory mite *Parasitusbi tuberosus* is effective against *Heteropezapygmaea*, first and second instar of *Lycoriella solani,* nematodes and springtails. Similarly, *Parasitusbituberosus* also assist to reduce the emergence of adult *L. solani* when larval population becomes low (Al-Amidi *et al.,* 1990). Predatory mite *Hypoaspis* (Acari: Hypoaspidae) can control sciarids and phorids in small scale laboratory trials and in some semi-field trials with no later resurgence issue(Chambers *et al.,* 1993; Jess and Kilpatrick, 2000; Jess and Bingham, 2004). It had demonstrated that the better control of these pests was achieved by using *Hypoaspis miles* as compare to *Steinernema feltiae* in both field and glasshouse conditions. Therefore, commercially availability of *H. Miles* has been considering as the better efficacy for controlling of both sciarid and phorids (Jess and Kilpatrick, 2000).

(iii) Insect parasitoids.

Parasitoids are any living organisms that are smaller in size than their hosts and have close association with their hosts. Mainly, immature stages (larva) of parasitoids developed within or on the body of hosts, which they eventually kill their hosts. For instance, it was reported that *Synaldisconcolor* parasitized the larvae of mushroom phorid (*Megaselianigra*). The parasitized *M. nigra* larvae continued to eaten up and developed normally until the pupation stage of metamorphosis. Generally, it is mostly observed in sequentially planted crops. Due to which, parasitism on pests of current crop will provide overall reduction of insect population in future crops also (Hussey *et al.,* 1969). Parasitoid wasp (*Orthocentrusbrachycerus*) also plays an important role for the controlling of *Neoempheria* larvae. The plot containing parasitoid wasp was effectively controlled the larvae of *N.*

carinata. Practically, it was reported that population of *Neoempheria* was found in less number in parasitoid treated plots compared to untreated plots in the next generation (Mukai and Kitajima, 2019; Watanabe *et al.*, 2020).

(iv) Beneficial Nematodes.

In mushroom cultivation, several entomopathogenic nematodes are used to control fly pests associated with mushrooms. Beneficial nematodes are used to kill the fly larvae; it can kill the host directly. Entomopathogenic nematodes are fit for the biological control strategies that have no adverse effect on mushrooms and environment (Navarro and Gea, 2014). The two species of insect-parasitic nematodes (*Heterorhabditis heliothidis* and *Steinernema feltiae*) were reported more successful against mushroom flies. It was reported that the larva of Phoridae, Cecidomyiidae and Sciaridae were more susceptible to parasitism by both insect-parasitic Rhabditid nematode species (Richardson, 1987).

Similarly, *Howardulahusseyi*, an obligate parasite, used to control the larvae of Phorid fly (*Megaselia halterata*) that enters and reproduces within the body of fly larvae (Fig. 14). As the nematodes grow inside the fly, they consume the reproductive system of the fly. Thus, the infected female flies produce few or no offsprings. Later, the nematodes are releasing back into the compost, when the female fly attempts to lay her eggs and ready to invade the larvae of other phorids (Richardson and Chanter, 1979; Keil and White, 2004; Rinker, 2017).

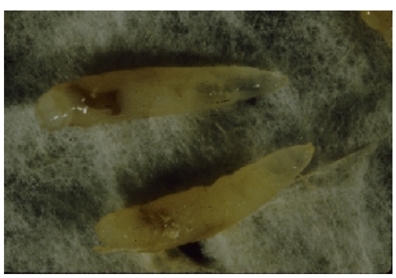


Fig. 14. Nematodes inside the Phorid larvae (Rinker, 2017).

These nematodes are typically applied through irrigation water. These nematodes prefer to attack young pupa or large fly larvae, about 12-16 days from egg laying. The nematode enters into the fly larvae and release infective bacteria into the body and eventually kills the fly larvae. These larvae either go through natural opening of the insect larvae or bore through the body of insects. As the fly larvae die, nematode will reproduce more young ones (Rinker *et al.*, 1995; Rinker *et al.*, 1997).

Botanical Control. Botanicals are considered as most popular and intensively used input methods in IPM to control several pests during mushroom cultivation practices. It was mentioned that 8 botanical materials were used against flies and several pests associated to mushrooms. Among all, 2 are neem-based products, Neemazal and Green neem oil and 6 are hot-water plants' extract, namely *Inula viscosa* L., *Melisa officinalis*, *Ononis natrix*, *Origanum onites*, *Pimpinella anisum*, and *Teucrium divericatumsieber*. These products were evaluated to control mushroom phorid fly by soil drench method, applied in soil up to 10 cm as larvae can be found up to 10 cm from the soil surface.

All these botanical treatments were compared with negative (water treated) and positive (chlorpyrifos-ethyl-treated) controls. Neem treatments (Neemazal and Greneem oil) gave better result with negative control for the reduction of adult emergence as compared to positive control. Whereas, Neemazal and *O. onites* extracts had significantly lowers the larval and sporophore damage rates with negative control compare to the positive. However, there were no significant differences were noted between Greneem oil, *Pimpinellaanisum* L. extract and chlorpyrifos-ethyl treatments. Thus, hot-water extracts of *Origanum onites*, *Pimpinella anisum* and neem products considered as the potential alternatives to synthetic pesticides for the management of mushroom flies (Erler *et al.*, 2009).

Chemical Control. Chemical method of pest control considered as the most popular component of Integrated pest management (IPM) approach, in which both synthetic and/or naturally derived chemicals are used to control the different pests of mushrooms. Chemical insecticides are typically used in production area, work area, and surface area where the pests will rest or swarm (Table 1).

Table 1: Different pesticides/chemicals used to control several pests associated with mushrooms.

Pests	Pesticides/ Chemicals	References
Sciarids,	Dimilin (diflubenzuron), Malathion, cyromazine, Permethrin (Do not use permethrin when mushrooms are present).	(Staunton *et al.*, 1999)
Cecid Larva	Lindane (γ-HCH) in mushroom substrate during the last turn of composting	(Hussey *et al.*, 1960).
Sciarid and Cecid	Fenpropathrin, Cyhalothrin, Permethrin, Cyfluthrin, Cypermethrin, Flucythrinate, Tau-fluvalinate, Fenvalerate, Deltamethrin	(Tian *et al.*, 2020).
Phorids	Deltamethrin, spinosad, trichlorphon, malathion and permethrin. Sudol (Fenvalerate) kills larvae of pests in empty mushroom houses/rooms and on utensils.	(Staunton *et al.*, 1999; Babar *et al.*, 2012)
Cyllodes sp., *Drosophila* sp.,	Carbaryl, Cypermethrin, methomyl at appropriate dose and methods.	(Jompong *et al.*, 2015)

Dasyses sp., and mites		
Flies, spiders, bugs, fleas, mites and larvae of insect pests	Bendiocarb and diflubenzuronin. Diflubenzuron either drenched onto casing or incorporated in compost.	(Staunton and Dunne, 2001; Stoddart *et al.*, 2004).
Insect pests, mites, diseases, nematodes and weeds	Fumigation of Methyl bromide (a pre-plant broad spectrum fumigant), sulfotep (Bladafum), sulphur, sodium cyanide, calcium cyanide and sulphuric acid.	(Davis, 1938; Staunton and Dunne, 2001; Duniway, 2002; Singh and Sharma, 2016)
Tarsonemid mites	Fumigation of greenhouse/mushroom house with methyl bromide for several hours. OR, Spraying with 0.01% Dicofol inside the empty rooms	(Hussey and Gurney, 1967)
Nematodes and other insect pests	Diflubenzuron (Dimilin), Deltamethrin (drenching), isothiocyanates, and methyl isothiocyanate	(Ploeg, 2008; Singh and Sharma, 2016)
Disinfectants	Sodium hypochlorite, formaldehyde, Potassium Permanganate, Iodine, Chlorinated Trisodium Phosphate, Ortho-phenylphenol	(Staunton and Dunne, 2001; Stoddart*et al.*, 2004)

The chemical method of pests control will creates several long-term environmental hazards, which becomes also toxic to beneficial living organisms including human also. Even, traces of the synthetic chemicals might lead to chronic and neurotoxicity in human (makundi, 2006; Das *et al.* 2021).

It was found that insecticides such as carbaryl, chlorpyrifos, cypermrthrin, endosulfan, methomyl and several pyrethroids have higher amount of chemical residues settled in the mushrooms, soil and water bodies (Jompong *et al.*, 2015). Brewer and Keil (1989a, b), reported that Sciarid fly was resistant to permethrin and diclorvosadulticides. However, the application of Dimilin at normal rate have found to be in the reduction of mushroom yield by 7-8% (Staunton *et al.*, 1999).

Spraying of Mushroom House

It becomes essential to spray the mushroom house with appropriate chemicals about 2 weeks before the compost filling to get rid from several insects, mites and other pests that might left on the preceding crops. It needs to fumigate or sterilized the house with fumigants such as Formaldehyde or sulphur. It is pertinent to mention that quarter of formaldehyde is used for one pound of permanganate of pot ash for fumigation purpose. For sulphur fumigation, the rate of sulphur should be 5 to 6 pounds per 1000 cubic feet of air space for effective control of mushroom pests (Davis, 1938).

Mechanical Traps. For monitoring of several phytophagous pests during crop production, different colored sticky traps are used, which assist to identify the appropriate time to follow several management practices to control harmful pests. Light traps are also used to attract the mushroom flies (Davis, 1938; Górska-Drabik *et al.*, 2011). Table 2 presents the efficiency of different colored sticky traps against three different fly species.

Table 2: Number of mushroom flies caught on different colored sticky traps in both growing periods.

Fly species	Growing period I			Growing period II		
	Yellow	Blue	White	Yellow	Blue	White
Megaselia halterata	10.5±1.2	9.0±2.5	2.5±0.4	9.6±1.6	11.3±3.1	4.1±0.6
Lycoriella ingenua	96.5±14.8	59.9±13.3	10.5±1.3	104.3±12.6	56.7±8.0	13.8±3.3
Scatopse spp.	25.3±3.0	23.4±3.0	3.9±0.4	24.7±5.2	22.1±4.3	4.7±0.8

Source: Sahin *et al.*, (2016).

The table illustrates the yellow and blue colored sticky traps able to attract more number of adults flies compared to the white. It depicts that the highest numbers of *Lycoriella ingenua* and *Scatopse* spp. were more attracted towards the yellow sticky traps followed by blue and white traps, consequently in both growing periods. However, *Megaselia halterata* was attracted more towards the yellow traps in the first growing period, but it was attracted more towards blue sticky traps in the second growing period. It was found that the yellow sticky traps becomes more effective against all three fly species followed by blue traps, whereas white traps found to be have least attractive ability to attract these flies compared to yellow and blue traps.

Heat Sterilization (Physical Method). Heat sterilization is one the best methods for the eradication of mushroom pests in small spaces before the house filled with mushroom compost. The major source of heat sterilization may be through steam, or electricity. Most of the microbiological text books state that the temperature of 250°F (121°C) becomes most appropriate for the steam heat sterilization process against microorganisms. For sterilization of substrates, temperature between 120° to 125°F is required for few hours to get rid from insect pests, mites, nematodes and pathogens (Davis, 1938; Kurtzman, 2010).

For instance, Treschow (1944) treated the substrate of Norway spruce needle litter in clay pots in different temperature of 60°C, 80°C, 100°C and 120°C for 60 minutes before spawnin. He reported that the highest yield was recorded at 60°C (242g/pot), followed by

80°C (97 g/pot), control treatment (40 g/pot), 100°C (22 g/pot) and 120°C (no yield).

Pasteurization of Compost (Physical Method). Raw compost substrate contains several types of undesirable pathogenic microorganisms, including nematodes, spores of moulds and resting stages of several insect pests. Hence, it needs to proper pasteurize the substrate of mushroom to prevent infestation by several pests in mushroom compost (Coles and William, 2002). By the supporting evidence, it was reported that *Geotrichum candidum*, *Agaricus bisporus*, *Verticillium malthousei*, *Mycogone perniciosa* and *Trichoderma viride* were eliminated from infected soil and substrate medium when treated at 54.4°C for at least 30 minutes (Wuest *et al.,* 1970).

For the pasteurization substrate, 60°C temperature for four or more hours is appropriate for the pests control in mushroom. The substrate has ability to produce heat from itself when the pasteurization of substrate begins. Consequently, heat produce by substrate itself from inside and heat provided from outside through steam acts as best way for compost pasteurization, which becomes successful to killing seeds, insect pests, nematodes and other harmful organisms. Thereafter, it needs to add more fresh air on substrate for some days to cool the compost (Kurtzman, 1979; Kurtzman, 2010).

Future Prospects and Strength of the Study

One of the major constraints in mushroom production is the damage caused by several pests, particularly arachnids, insects, and nematodes. In the past few decades, number of pest species has developed the resistance ability against different pesticides due to the powerful selection of pesticides imposed on the pests. Since, pesticides constitute the major tool for the control of different types of mushroom's pests; therefore, there shall be a continuous need for the new and effective synthetic chemicals. However, that may not be readily available due to the high costs of production, and pressure from environmental groups. Therefore, it shall be more urgent to adopt ecological based approaches to control mushrooms associated pests. Ecological pest management strategies are appropriate, environmentally sound, sustainable, and cost effective in maintaining the pest's population below the economic thresholds level.

In Future, adoption of all elements of IPM and introducing the application of information and communication technology in mushroom production enterprises might have significant results for the protection of mushrooms against several biotic and abiotic stresses. For the future prospective, it must be crucial to focus on research facilities and training of farmers, scientists and extension workers in order to cope with the challenges ahead. Therefore, these steps might have potential to enhance the production of mushrooms and also assist to manage the pests in eco-friendly manner. Therefore, it might significantly increase the yield and quality of mushrooms in upcoming days.

CONCLUSION

To conclude, Mushroom farming is becoming the most popular enterprise nowadays. Farmers from different parts of the world are intensively growing different species of mushrooms like field and horticultural crops. However, one of the serious threats during mushroom cultivation is severe infestation by several pests, leading to huge mushrooms damage resulting into heavy economic loss. For effective and efficient management of pests, IPM acts as an ecological tool, which incorporates preventive and restorative measures to keep the crops free from pests with minimum risk towards ecosystem. It is advisable to rely less on chemical methods to control pests because excessive use of chemicals leads to create long term negative impacts on natural ecosystem, and has adverse effects for both beneficial living organisms and human also.

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