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Review on Maize Chlorotic Mottle Virus: Distribution, Host Range, Transmission Mechanisms and Management Options

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Abstract
Plant virus diseases are serious constraints to the productivity and profitability of a wide range of crops. Epidemics of existing plant virus diseases and the emergence of novel virus diseases have become a serious threat to subsistence and commercial agriculture. The knowledge of virus transmission and its survival helps to understand how the disease transmits from infected plant to healthy, where it reserved, and this will lead to identify the most important variables and focus efforts to develop sustainable management strategies. *Maize chlorotic mottle virus* (MCMV) is transmitted from location to location, and from plant to plant through various mechanisms (mechanically, seed, insect vectors, and soil) and many kinds of wild grass and cultivated crops, maize residue are used as its reservoirs. Different weed species and cultivated plants used as alternate hosts, and soil and seed transmissibility of MCMV are epidemiologically important and contribute to maintaining virus inoculum available in the absence of maize in the field and increase the chances of continuing its survival. Integrated disease management approach, regular field monitoring, assessment of virus symptoms, and rouging-out diseased plants are recommended to prevent further spread by insect vectors. Apart from this, because the disease is still widespread in various countries, intensive MCMV recruitment, combined with integrated disease management, requires ongoing practice in countries where MCMV is prevalent and in those countries that have not yet reported MCMV.
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1. Introduction

Maize (*Zea mays* L.) is the main staple food in Latin America and Sub-Saharan Africa (Iken and Amusa, 2004). The crop is ranked the third most important cereal plant after wheat and rice (Khalili *et al*., 2013). Presently maize is cultivated throughout the year in almost every part of the world. The potential yield of maize per unit land area is highly dependent upon fertility levels, plant population, management practices, and the inherent potential of the variety adapted to that area.

Plant viruses are among the major factors that affecting food production worldwide and cause vast economic losses. It results in the loss by limiting plant produce quality and quantity (Thresh, 2006; Van der Vlugt, 2006) and have an estimated economic impact of more than $30 billion per year (Sastry and Zitter, 2014). Globally, there are more than 32 maize infecting viruses recorded on maize. Among them, *Maize chlorotic mottle virus* (MCMV) is one of the most devastating maize productions worldwide. Hence the objective of this paper is to overview the MCMV global distribution, host range, transmission mechanism, and its management options.

Discussion

2.1. Maize chlorotic mottle virus (MCMV) and its strains

MCMV is the only identified member of the genus *Machlomovirus* in the family *Tombusviridae* (King *et al.*, 2011). There are several strains of MCMV have been identified. MCMV-NE is the isolate from Nebraska (Stenger

Uyemoto, 1983) ... E) share 99.5% Nucleotide sequence identity, a clear indication the two isolates are related (Nutter *et al*., 1989' Stenger and French, 2008). MCMV isolates from Thailand were closely related to China strains with 98-99.6% sequence similarity (Wu *et al*., 2013). The nucleotide sequence similarity of MCMV isolates from East African countries is 99% (Mahuku et al., 2015), that the whole region has similar MCMV viruses interacting mainly with SCMV. Kenyan isolates had 95-98% sequence similarity (Wangai., *et al*., 2012). Ethiopia isolate was similar to East Africa isolate with 99% similarity (Mahuku *et al*., 2015). Rwanda, Kenya, China isolates were identical with 99% and 96-97% with USA isolates (Adams *et al*., 2014).

2.2. Yield loses caused by MCMV

MCMV infects maize plants and causes significant losses in maize production. Under natural field conditions, MCMV causes 10-15% crop loss and up to 59% loss under inoculated conditions (Castillo and Loayza, 1977). When MCMV co infects maize plants with other maize viruses from the family *Potyviridae*, such as maize dwarf mosaic virus (MDMV) (genus: *Potyvirus*), Sugar cane mosaic virus (SCMV) (genus: *Potyvirus*), or Wheat streak mosaic virus (WSMV) (genus: *Tritimovirus*), their synergistic effect causes a more severe disease called Maize lethal necrosis (MLN), previously known as Corn Lethal Necrosis which leads to almost 100% field loss (Uyemoto *et al*. 1980; Goldberg and Brakke, 1987; Xie *et al.*, 2011). When MCMV co-infects maize with any potyvirus infecting maize plants, a synergistic interaction occurs, causing a severe disease (Fig. 1) and yield losses. MCMV can cause 91% yield loss occurs in co-infection with either MDMV or *Wheat streak mosaic virus* (WSMV) (Niblett and Claflin, 1978). In Africa, MCMV is a serious disease of maize from its first outbreak in Kenya (Wangai *et al*., 2012) to the present (Regassa *et al*., 2020; 2021). In Africa 30-100% loss in co-infection with SCMV (Wangai *et al*., 2012, Mahuku *et al*., 2015; Guide *et al*., 2018; Regassa *et al*., 2020).

Fig. 1. MCMV co-infection with SCMV causing severe damage on maize under natural field condition

2.3. MCMV symptoms

Depending on the host genotype, MCMV infection symptoms range from mild to severe chlorotic mottle, leaf necrosis, stunted growth, a shortened male inflorescence with few spikes, malformed or partially filled ears, and premature death of plants (Niblett and Claflin, 1978; Uyemoto *et al*., 1981; Regassa *et al*., 2021).

When MCMV co-infects maize with a potyvirus infecting maize, the infected maize plants under field condition show a various range of symptoms, such as chlorotic mottling of the leaves (Fig 2 a and b), typically starting from the base of the young leaves in the whorl and extending upwards toward the leaf tips. The leaves can experience necrosis at the leaf margins that progress to the mid-rib resulting in drying of the whole leaf (Fig 2 d). Other symptoms include premature aging of the plants and mild to severe leaf mottling. Severely affected plants form small cobs with little or no grain set (Fig 2 f and g). The entire crop can frequently be killed before tasseling (Niblett and Claflin, 1978; Uyemoto *et al*., 1980, 1981; Wangai *et al*., 2012; Regassa *et al*., 2021).

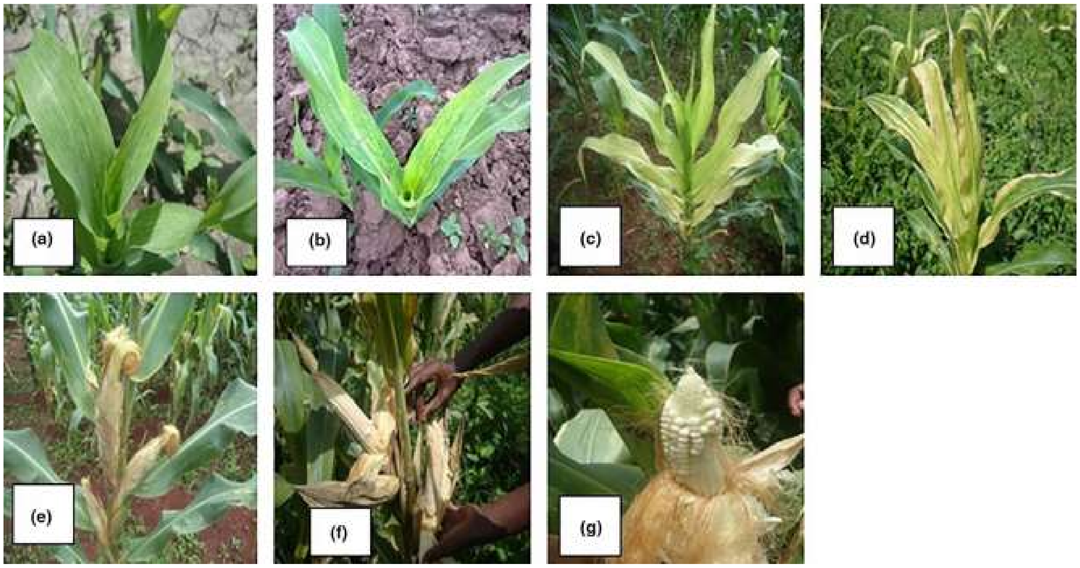

Fig 2. MCMV co-infection with SCMV and symptoms commonly observed under natural field condition: (a) chlorotic, (b and c) mild to severe leaf mottling, (d) necrosis of leaf margins, (e) drying cob, (f and g) poor or no grain filling. Source: Regassa et al. (2021).

2.4. History and Global distribution of MCMV

MCMV was first described in maize from Peru in 1973 and reported in 1974 (Castillo and Hebert, 1974) and thereafter was reported on maize plants in different countries of South America, North America, Europe, Asia and Africa. In Africa, MCMV was first occurred in Kenya in 2011 and reported in 202 (Wangai *et al*., 2012), since then have been reported and widespread in other East African countries. The following Table (Table 1) provides the year in which samples first tested positive for MCMV in each country it has reported in.

Table 1. MCMV global distribution

Continent/Country	Earliest report	Reference
SOUTH AMERICA		
Peru	1973	Castillo and Hebert (1974)
Argentina	1982	Teyssandier and Bo (1983)
Ecuador	2015	Quito-Avila *et al*. (2016)
NORTH AMERICA		
USA	1976	Niblett and Claflin (1978)
Mexico	1984	Gordon *et al*. (1983)
Hawaii	1990	Jiang *et al*. (1992)
Kansas	1977	Nault *et al*. (1978)
Nebraska	1981	Doupnik *et al*. (1982)
Texas	1978	Kessler (1979)
EUROPE		
Spain	2015	Achon et al. (2017)
ASIA		
Thailand	1982	Klinkong and Sutabutra (1983)
China	2011	Xie *et al*. (2011)
Yunnan		Wang *et al*. (2014)
Taiwan	2014	Deng *et al*. (2014)
AFRICA		
Kenya	2011	Wangai *et al*. (2012)
Tanzania	2012	Mahuku *et al*. 2015b
Uganda	2013	Mahuku *et al*. 2015b
Rwanda	2013	Adams et al. (2014)
Democratic Republic of Congo	2013	Lukanda *et al*. (2014)
Ethiopia	2014	Mahuku *et al*. (2015a)
South Sudan	2014	Mahuku *et al*. 2015b

2.5. MCMV host range

2.5.1. Natural alternative hosts

Earlier, maize was reported as the only known natural hosts of MCMV (Scheets, 2004), recent studies, however, have identified MCMV from sugarcane; finger millet, sorghum, Napier grass and Kikuyu grass (Wang *et al*., 2014; Kusia *et al*. 2015; Mahuku *et al*., 2015; Regassa *et al*., 2021). Our recent study (Regassa et al., 2021) showed that the *Poaceae* family had the highest number of grass species that were alternate hosts for MCMV, and *Cyperus cyperoids* and *Cyperus cyperoides* from the *Cyperaceae* family were naturally infected by MCMV (Regassa *et al*., 2021). Most of the natural alternative hosts identified were annual and perennial grasses in nature (Table 2), and common in the maize growing areas.

Table 2. Natural alternate hosts of MCMV identified

Family	Species	Life cycle	Type
Cyperaceae	*Cyperus rotundus* L.	Perennial	Sedges
Cyperaceae	*Cyperus cyperoides* L.	Perennial	Sedges
Poaceae	*Snowdenia polystachya* (Fresen.) plig.	Annual	Grasses
Poaceae	*Cynodon nlemfuensis* Vanderyst.	Perennial	Grasses
Poaceae	*Digitaria sanguinalis* (L.) Scop.	Annual	Grasses
Poaceae	*Echinochloa colona* L.	Annual	Grasses
Poaceae	*Oplismenus hirtellus* L.	Perennial	Grasses
Poaceae	*Pennisetum purpureum* Schumach.	Perennial	Grasses
Poaceae	*Phalaris paradoxa* L.	Annual	Grasses
Poaceae	*Sorghum bicolor* L.	Annual	Grasses
Poaceae	*Saccharum officinarum* L.	Perennial	Grasses

Source: Regassa et al. (2021)

Different types of MCMV symptoms were observed on different plant species of its alternative hosts. The symptoms observed included mosaics, mottling, yellowing, necrosis that develop from leaf margins to the mid-rib, and purple discoloration of leaves. For instance, MCMV symptoms on *Cyperus cyperoids* and *Snowdenia polystachya* were expressed as yellowing, while it showed mosaic and chlorotic symptoms on *Oplismenus hirtellus* (Fig.2) (Regassa *et al*., 2021).

Fig. 3. Maize chlorotic mottle virus (MCMV) on naturally infected different alternate hosts shows yellowing and mosaic symptoms.

2.5.2. Experimental host range

Bockelman *et al*. (1982) has identified a broad range of MCMV experimental host range that includes at least 19 grass species, but it does not infect dicots. According to Sheets (2004), 73 grass species in 35 genera have been tested for susceptibility to virus strains MCMV-Kansas, MCMV-Peru, or both (Table 3).

Table 3. Plants tested for susceptibility to strains of MCMV (Scheets, 2004)

Immune genera	Susceptible genera	Genera with both immune and susceptible species
Axoponus Chloris	*Andropogon*	*Agropyron*
Elymus	*Avena*	*Bromus*
Festuca	*Bouteloua*	*Cenchrus*
Lolium	*Buchloe*	*Cynodon*
Oryza	*Calamovilfa*	*Dactylis*
Paspalum	*Eleusine*	*Digitaria*
Poa	*Eragrostris Euchlaena*	*Echinochloa*
Saccharum	*Hordeum*	*Panicum*
	Secale	*Phalaris*
	Sorgastrum	*Setaria*
	Sorghum Spartina	*Zea*
	Tripsacum Triticum	

The recent MCMV experimental host range study (Regassa *et al*., 2021) revealed that among the 39 weed species tested for reaction to MCMV using artificial inoculation in the greenhouse, 20 species were susceptible to MCMV infection (Table 4). Cereal crops (barley and wheat) were also experimentally infected by MCMV (Fig 3, G and H).

Fig 4. Maize chlorotic mottle virus (MCMV) symptoms (mild chlorotic, yellowing, necrosis starting from leaf merges to mid-rib) on mechanically inoculated grass weeds and cereal crops (A = dinebra retroflexa, B = Setaria verticillata, C = Cyperus assimilis, D = Digitaria ternta, E = Oplismenus hirtellus, F = Sorghum arundianaceum, G = wheat, H = barley.

Table 5. MCMV experimental host (Weed species) identified by artificially inoculation in greenhouse

Family name	Species name	Life cycle	Type of weed
Cyperaceae	*Cyperus assimilis* Steud.	Annual	sedges
Cyperaceae	*Cyperus esculentus* L.	perennial	sedges
Cyperaceae	*Cyperus rotundus* L.	Perennial	Sedges
Poacceae	*Cenchurus ciliaris* L.	perennial	Grasses
Poacceae	*Cyndon nlemfuencis*Vanderyst.	Perennial	Grasses
Poaceae	*Andropogon abyssinicus* (Fresen.) R. Br.	Annual	Grasses
Poaceae	*Cyndon dactylon* (L.) Pers.	Perennial	Grasses
Poaceae	*Denebra retroflexa* (Vahl.) panzer	Annual	Grasses
Poaceae	*Digitaria abyssinica* (A. Rich) Stapf	Perennial	Grasses
Poaceae	*Digitaria ischaemum* (Schreb.) muhl.	Annual	Grasses
Poaceae	*Digitaria ternate* (A. Rich.) Stapf	Annual	Grasses
Poaceae	*Echinocloa colona* (L.) Link	Annual	Grasses
Poaceae	*Eleusine indica* L. Gaertn.	Annual	Grasses
Poaceae	*Eragrostis cilianesis* (All.) Lut.	Annual	Grasses
Poaceae	*Pennisetum ramosum* (Hochst.) Schweinf.	Annual	Grasses

Family name	Species name	Life cycle	Type of weed
Poaceae	*Phalaris paradoxa* L.	Annual	Grasses
Poaceae	*Setaria pumila* (poir.) Roem. & schult.)	Annual	Grasses
Poaceae	*Setaria verticillata* (L.) P.Beauv.	Annual	Grasses
Poaceae	*Snowdenia polystachya* (Fresen.) pilg	Annual	Grasses
Poaceae	*Sorghum arundinaceum* (Desv.) Stapf	Annual	Grasses

Source: Regassa et al. (2021)

2.6. Mechanisms of MCMV transmission

2.6.1. Mechanical Transmission

MCMV is transmitted mechanically by sap. Mechanical transmission occurs when a plant comes in contact with other plants and leaves rub together or by humans' interferences like tools/hands/clothing. It involves the introduction of an infective virus or biologically active virus into a suitable site in the living cells through wounds or abrasions in the plant surface. Spreading viruses by the mechanical method is generally used for experimental purposes under laboratory/greenhouse conditions.

2.6.2. Insect vectors

The transmissions of viruses from plant to plant by vectors provide the main method of spread in the field for many viruses including MCMV that cause severe economic loss (Hull, 2014). In Ethiopia, studies on the MLN (MCMV is the main component) distribution and factors associated with its epidemic show that the spread of MLN causing viruses (MCMV and SCMV) are linked to the free movement of insect vector and continuous availability of the host plants (Regassa *et al*., 2020). In the United States mainland, MCMV has been reported to be transmitted by six different species of chrysomelid beetles, including the cereal leaf beetle (*Oulema melanopa*), corn flea beetle (*Chaetocnema pulicaria*), flea beetle (*Systena frontalis*), southern corn rootworm (*Diabrotica undecimpunctata*), western corn rootworm (*Diabrotica virgifera*) and northern corn rootworm (*Diabrotica longicornis*) (Jiang *et al*., 1992; Nault *et al*., 1978).

The other vector that transmits MCMV is maize/ corn thrips, *Frankliniella williamsi* Hood (Thysanoptera: *Thripidae*) has been identified to be the main vector (Cabanas *et al*., 2013) in Hawai, USA. Maize thrips transmit MCMV in a non-persistent manner. Both larvae and adults of corn thrips transmitted MCMV for up to 6 days after acquisition, with decreasing rates of transmission as time progressed.

2.6.3. Seed Transmission

MCMV is also transmitted by seed. The rate of MCMV seed transmission observed by Jensen et al. (1991) who evaluated 42,000 seedlings and found a 0.04% transmission rate in Hawaii, USA. Quito-Avila et al. (2016) from Ecuador reported 8 and 12% seed transmission of MCMV. Zhang et al. (2011) reported MCMV seed transmission of 2 seeds in 600 (0.33%) in Chinese maize. The recent MCMV seed transmission study (Regassa *et al*., 2021) showed the mean seed to the seedling transmission rate of MCMV was 0.073% with a range of 0 to 0.17% among 20 different maize varieties studied. Fourteen maize genotypes had some levels of seed transmission (0.03%–0.017%) for MCMV. Seed transmission rates of the viruses were influenced by the seed lot and maize varieties used (Regassa *et al*., 2021).

2.6.4. Transmission through soil and plant residue

Transmission in soil water or crop residues has been suggested for MCMV, and there are a number of reports of increased disease pressure after heavy rainfall and in soils with a higher water capacity (Jensen, 1991; Uyemoto, 1983). Mahuku et al. (2015) found that planting clean seeds in the soil from MLN-affected areas resulted in 69% MCMV infection. Our current study also confirmed that low soil transmission (4.24-13.5%) MCMV can be transmitted from infested soil to newly raised maize seedlings and it also reserved in maize residues (Regassa et al., unpublished data). Similar findings were previously reported on MCMV transmission through soil (Nyvall, 1999). It also reported that MCMV can be transmitted through infected plant residues that play important roles in the survival of the virus especially when maize is planted during the off-season (Uyemto, 1983; Montenegro and Castillo, 1996).

2.7. Management of MCMV

Plant virus diseases including MCMV are intrinsically difficult to manage directly by measures such as direct use of chemical pesticides, an integrated management options which include the use of disease-resistant crop varieties, the uses of cultural practices like crop sanitation and removal of infection sources, use of virus-free seeds and chemical pesticides such as seed treatment and foliar spray to indirectly control vector insects is the most feasible option.

The most effective control for MCMV has been achieved through the integration of cultural practices with insecticides and host resistance (Nelson *et al.,* 2011). Alternatively, crop rotation with non-maize crops has been shown to reduce the incidence of MCMV the following year (Phillips *et al*., 1982; Uyemoto, 1983). Maize Producers are advised to practice crop rotation for at least two seasons with alternative non-cereal crops such as potatoes, sweet potatoes, cassava, beans, bulb onions, spring onions, vegetables and garlic. Planting different crops each season will diversify farm enterprises. Manure and basal/top dressing fertilizers can be applied to boost plant vigor.

It is necessary to use good field sanitation methods, including weed control measures to eliminate alternate hosts for potential vectors (Wangai *et al*., 2012; Regassa *et al*., 2020, 2021). Infected foliar material should be removed from the field to reduce pathogen and vector populations. In Hawaii, USA producers of maize seed spray regularly after planting to control insects that spread the virus (Nelson *et al*., 2011). The use of tolerant or resistant varieties ultimately would be the most effective means of managing MCMV (Regassa *et al*., 2020). Superior resistance to MCMV is widely available in tropical maize seed stocks and provides the best control for this disease. The use of host resistance is the most desirable and feasible method in virus disease management. According to Nelson *et al*. (2011), trials performed in Hawaii in 2011 found many tropical inbred lines and varieties to be highly resistant to MCMV. Almost all temperate climate inbred lines and hybrids are highly susceptible to the virus (Nelson *et al*., 2011).

MCMV infested soil and infected maize residue play an important role in the survival, inoculum source and spread of MCMV. Thus, proper management of crop residues in the field after harvest is necessary to minimize the adverse effects of MCMV on maize production. Crop rotation is one of the ways of freeing the soil from MCMV disease. Therefore, as part of integrated management of MCMV, maize growers should remove all infected maize materials/residues from the field, ignore any activity that moves the soil from MCMV infected fields or infected maize residue from one place to another.

3. Conclusions and Recommendation

Because of the level of damage caused and potential of the disease to spread and cause tremendous losses in most major growing areas of the East African countries, MCMV which is the main component of MLN is currently considered as a high-risk emerging disease and given a top priority for intervention by research and crop pest regulatory authorities in the agricultural sector.

Plant virus disease management including MCMV has to be knowledge-based, and thus, it is important to know the geographical distribution and to understand the role of infected seed, alternate hosts, and insect vectors in the emergence and development of disease epidemics. MCMV transmitted from location to location, and from plant to plant through various mechanisms and many kinds of wild grasses and cultivated crops used as its reservoirs. MCMV infected seed, weed and cultivated plants are known as alternate hosts of MCMV are epidemiologically important and maintain the virus inoculum in the absence of maize crop in the field, and support the survival of the virus for continuous infection. Farmers and stakeholders involved in maize cultivation should take preventive measures by eliminating alternate host plants within and in the surrounding areas of maize fields, use virus-free and certified seed from known sources for sowing.

Different weed species and cultivated plants used as alternate hosts, and seed transmissibility of MCMV are epidemiologically important and contribute to maintaining virus inoculum available in the absence of maize in the field and increase the chances of continuing its survival. Therefore, regular field monitoring, assessment of virus symptoms, and rouging-out diseased plants are recommended to prevent further spread by insect vectors. Apart from this, because the disease is still widespread in various countries, intensive MCMV recruitment, combined with integrated disease management, requires ongoing practice in countries where MCMV is prevalent and in those countries that have not yet reported MCMV.

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