General Conclusion

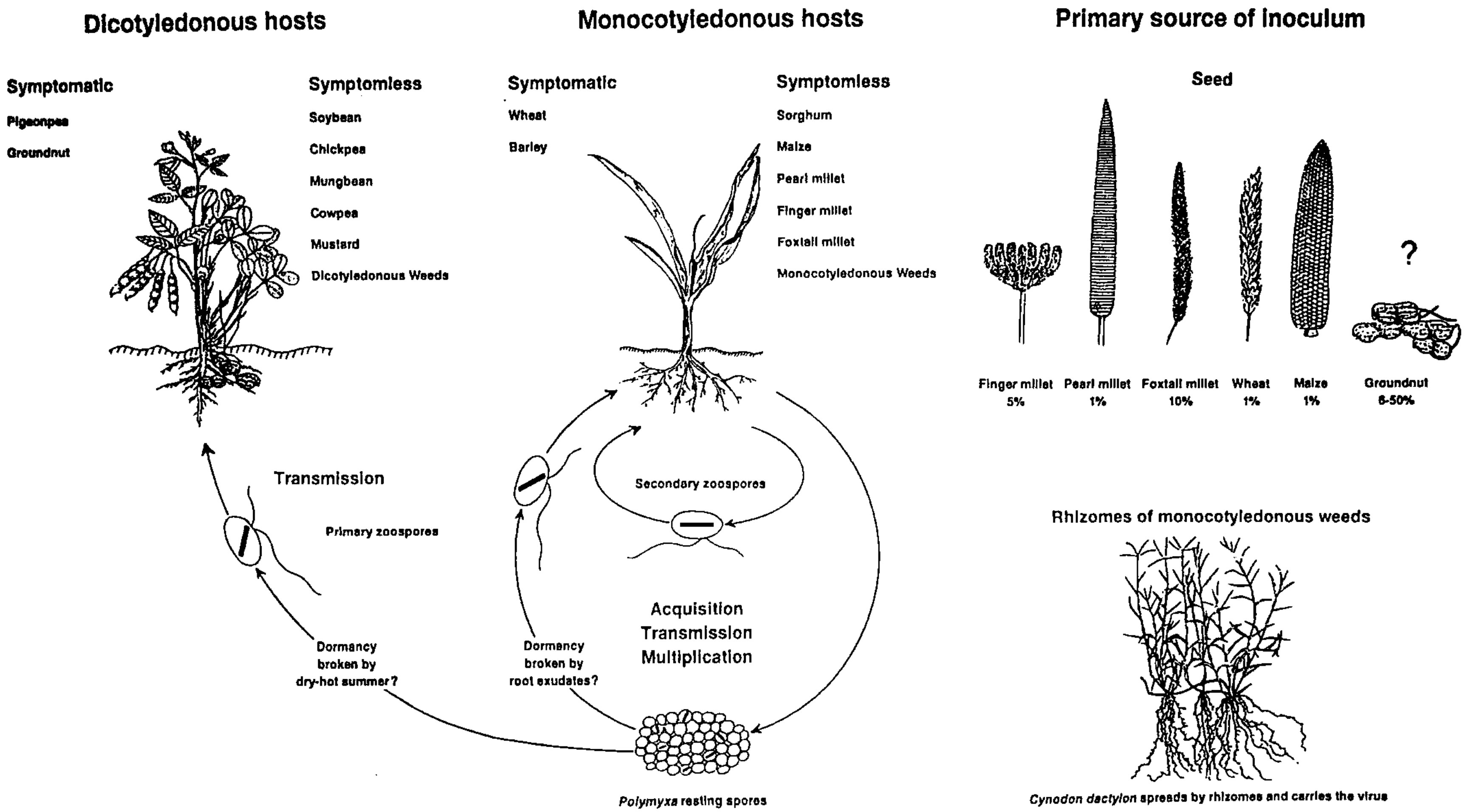

Figure 2. Life cycle of the Indian peanut clump virus (IPCV), an economically important seed-transmitted and soil-borne virus. The obligate parasitic plasmodiophorid, P. graminis, transmits IPCV to various monocotyledonous and dicotyledonous species.

General conclusion

The present work brought light on the complexity of the peanut clump disease epidemiology. The virus -IPCV-, its vector -*P. graminis*-, and their hosts interact with each other and are governed by various environmental factors (Fig. 1).

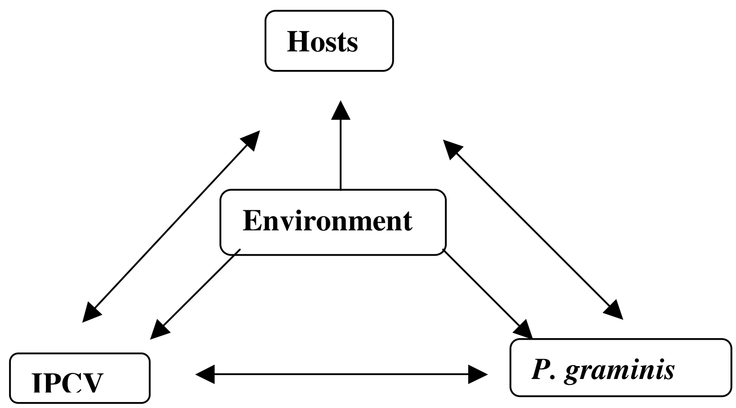

Figure 1: The complex relationship between IPCV, *P. graminis*, their hosts and the environment.

Disease life cycle

IPCV is an economically important seed transmitted and soil-borne virus with a wide host range. Peanut clump disease mostly occurs in light textured soils. Its epidemiology is peculiar in that the virus inoculum is maintained and perpetuated in some of the monocotyledonous hosts in which it causes little damages but when transmitted to susceptible crops such as groundnut, it causes and economically important disease. The study of peanut clump disease epidemiology was further complicated because the vector is an obligate parasite. Additionally, favourable hosts for the virus were not necessary the same for the vector and vice versa. Based on the epidemiological studies and the results of our experiments on the control of peanut clump disease through cultural practices, the Fig 2 is presented to illustrate the life cycle of IPCV. Fig. 3 gave a detailed approach of the disease life cycle at the level of the vector, *P. graminis*. These figures are commented below:

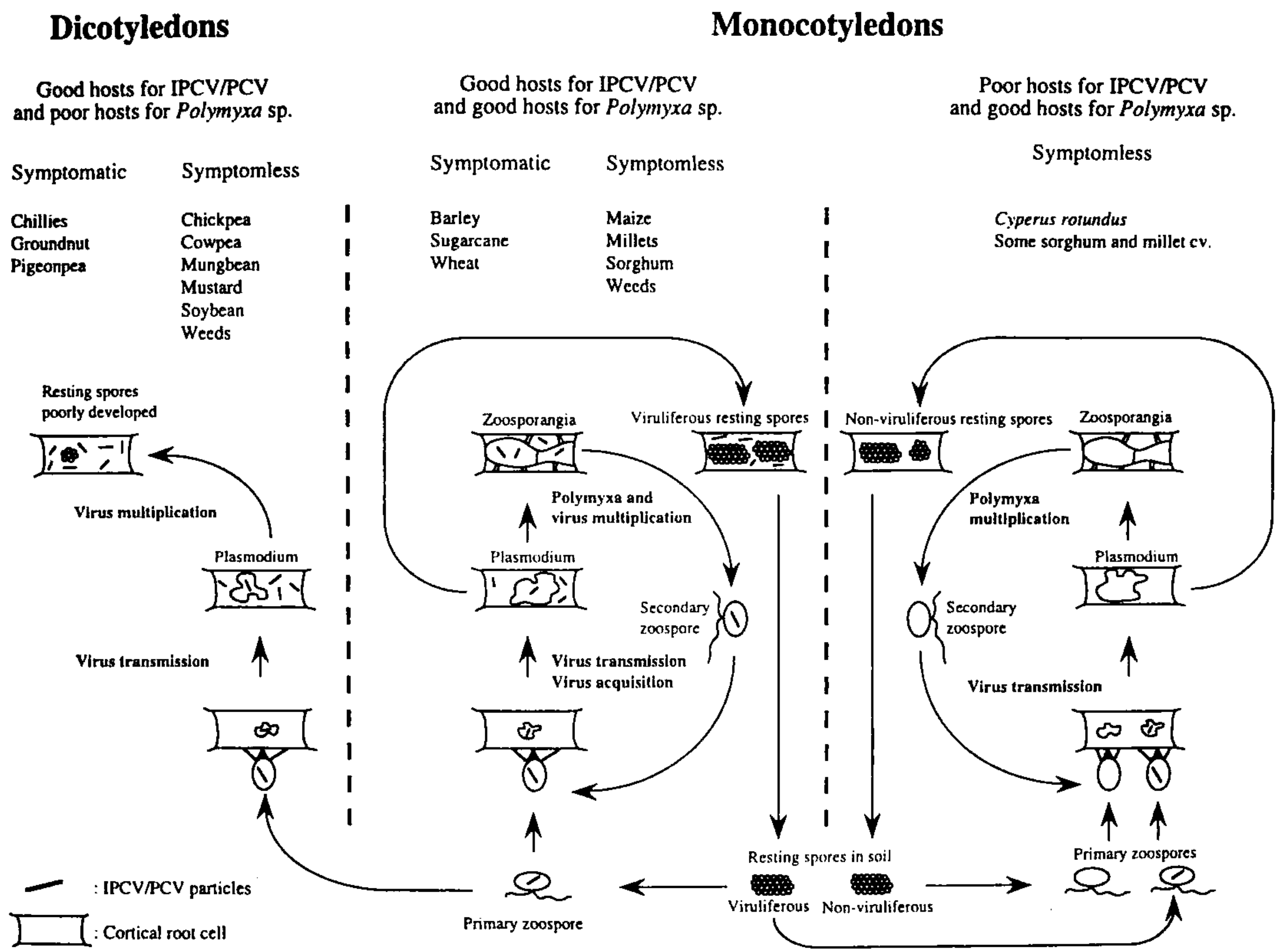

Figure 3. Life cycle of IPCV and its vector *Polymyxa graminis* in monocotyledonous and dicotyledonous hosts

- Dicotyledonous hosts do not permit extensive multiplication of *P. graminis* and are therefore considered as fortuitous hosts that will not contribute to perpetuation of virus inoculum. Indeed virus-infected groundnut roots or virus containing groundnut seed could not transmit or were a poor source of virus for the establishment of the disease. Rotation with such dicotyledonous hosts as mustard and marigold was correlated with low disease incidence.

- In contrast, monocotyledonous hosts such as sorghum, pearl millet, maize and various weeds, were found to be the preferred hosts for multiplication of *P. graminis.* Since they can also host IPCV, they are likely to contribute to the build up of viruliferous *P. graminis* inoculum potential in the soil. Today India is a major producer of maize (over 6 M ha/year), sorghum (10.2 M ha), and millets (12.8 M ha) (Anonymous, 1998). These crops are often rotated or intercropped with groundnut. These cereals are mostly grown in the rainy season under conducive conditions for *P. graminis* multiplication and are therefore considered as the main perpetuator of viruliferous inoculum. Seed of millets, maize and wheat and rhizomes of *Cynodon dactylon* are likely to serve as primary sources of virus inoculum for the establishment of the disease in new areas by supporting both virus and *P. graminis* multiplication.

- Certain monocotyledonous hosts such as *Cyperus rotundus* and some *Sorghum* and *Pennisetum* accessions, even though are excellent hosts for *P. graminis*, were found to be poor or transient hosts for the virus. Their role in the peanut clump disease life cycle is still unclear. Do they contribute to render *P. graminis* non-viruliferous? Heavy infestation by *C. rotundus* in a naturally infested field was not correlated with high disease incidence. Therefore we expect that such hosts may not contribute to increase in virus inoculum potential.

- Detailed studies under controlled conditions on the host range of *P. graminis* from tropical and subtropical regions of India confirmed these findings (Legrève, 1999). The author reported that only a trace of infection by *P. graminis* from tropical India occurred on wheat, barley, rice and groundnut. In the experiments that I conducted under field conditions and those conducted by Legrève under controlled environment, *P. graminis* from tropical India was mainly detected in sorghum, pearl millet and maize and it occurred also in few plants of finger millet. The crops that strongly support multiplication of *P. graminis* from tropical India all have a C4 photosynthetic pathway. In contrast, *P. graminis* from temperate areas, including subtropical isolates from Rajasthan in India, has been reported to develop well on

C3 plants such as barley, wheat and oats (Barr, 1979, Bastin *et al.*, 1989, Adams and Jacquier, 1994, Legrève, 1999). On the basis of this, we can conclude that IPCV and its vector are well adapted to the major monocotyledonous crops cultivated in the tropics.

- Virus transmission occurs in monocotyledonous crops even when climatic conditions are not conducive for infection of dicotyledonous crops during the post-rainy season. Temperatures do not limit IPCV multiplication because it can replicate at a wide temperature range, between 15 and 30°C (Reddy *et al.*, 1988). Though low temperatures are not conducive for *P. graminis* multiplication (Legrève *et al.*, 1998), temperatures prevailing during the post-rainy season in Andhra Pradesh appeared to be adequate for germination of sporosori, and consequently for virus transmission to wheat and barley. We suspect that specific stimuli produced by monocotyledonous hosts are involved in the break down of the dormancy of *P. graminis* resting spores.

The susceptible hosts

We have shown that the various crops studied, except sunflower, were all hosts for IPCV under natural environment. In addition to groundnut, IPCV was shown for the first time to cause diseases in such important crops as wheat, barley, pigeonpea and chilies. It also caused yield reduction in maize. Virus incidence varied greatly according to the crop. IPCV infection under field conditions is apparent only in crop plants in which symptoms are relatively severe. This is the case with groundnut, pigeonpea, wheat and barley crops when they are grown in an infested field under conducive conditions. By contrast, infection of grassy weeds, sorghum, and millets, is usually symptomless, indicating an ecologically balanced association. While agricultural activities results in the wide-spread dissemination of several pathogens, the distribution of the various IPCV isolates in different regions in India suggests that up to now the virus did not spread extensively to new areas. Specific association may have occurred between some of the *P. graminis* isolates and the various virus isolates. However the presence of two serotypes in the same field of a research station in Pakistan (Delfosse *et al.*, 1995) and the report of PCV spread in West Africa (Konaté and Barro, 1993) indicates that the risk of virus dissemination exists.

The desire of human beings to explore new areas for introducing various crop species has resulted in the movement of plant species from their centre of origin to new areas of the world. *Pecluviruses* have not been reported from South America, the centre of origin of *Arachis* spp. This study has shown that crop species that were recently introduced to the Indian sub-continent (groundnut, chillies, and maize) or crop species (barley, wheat, and pigeonpea) which were grown in marginal areas for their production, showed high virus incidence and severe symptoms following infection. Groundnut, chillies and maize are American in origin. The time of their introduction to India, probably the 15th century is still the source of controversy but it is a general consensus that their cultivation on significant scale in India was initiated about 150 years ago (Sinha and Bahgat, 1988, Norman *et al.*, 1984, Singh and Nigam, 1997). With this reasoning, at first sight, pigeonpea, wheat and barley may appear as exceptions. They were found to be highly susceptible to peanut clump disease. Wheat and barley were introduced to the Indian sub-continent some thousands of years ago while the centre of origin of pigeonpea is the peninsular India (van der Maesen, 1990). Pigeonpea is traditionally grown in poor soils with heavy texture where other crops do not perform well, or to prevent soil erosion (Nene, 1990). The pigeonpea growing areas mostly do not match those of groundnut, which requires light textured soils for adequate peg setting. It is possible that this study force pigeonpea to encounter a new pathogen in sandy areas, the apparently preferred soil texture for clump disease to occur at high incidence. A similar situation probably occurred with wheat and barley whose production areas in India are mostly located above the tropic of Cancer. Lower temperatures in the north of India are not conducive for high virus incidence in wheat and barley crops.

Sorghum, pearl millet and finger millet are ancient and traditional crops of the Indian agriculture. IPCV does not cause overt symptoms in these cereals and in graminaceous weeds. The millets and sorghum were introduced from western and eastern Africa (Norman *et al.*, 1984) where Pecluviruses have since been reported to occur (Thouvenel *et al.*, 1988 and Chatenet and Saeed, 19950. It is suggested that Pecluviruses are not typical groundnut viruses but actually viruses of the gramineae that possibly co-evolved in tropical and sub-tropical areas with wild grasses and cereal crops such as millets and sorghum. This hypothesis is reinforced by the fact that the vector of IPCV, *P. graminis* multiples well in pearl millet and sorghum.

Abiotic factors

The epidemiology of IPCV was found to be closely linked to the epidemiology of *P. graminis.* Various parallelisms were observed: (i) high rainfall resulted in high virus incidence but also induced high *P. graminis* incidence in monocotyledonous hosts, (ii) *P. graminis* from tropical India is favoured by relatively high temperatures in the range 23-30 °C (Legrève *et al*., 1998) and low temperatures (10-15°C) in post-rainy season resulted in low disease incidence in groundnut and pigeonpea crops, (iii) drought and heat during storage increases incidence of *P. graminis* in bait plants (Legrève *et al*., 1999). Groundnut crops sown after the dry and hot summer with the onset of monsoon rains were found to be severely affected by clump disease (Delfosse *et al*., 1996). These observations corroborate the hypothesis that peanut clump disease epidemiology is closely influenced by the ecological requirements of its vector as has been reported for other virus diseases transmitted by the genus Polymyxa (Schlösser, 1988, Usugi, 1988, Brakke and Langenberg, 1988, Adams, 1990, Goffart, 1992, Tuitert and Homeester, 1992, Ohto and Naito, 1997, Carroll *et al*., 1997).

Management

As a result of the research reported here I have been successful in devising cultural practices for managing peanut clump disease. These measures were based on the results of the experiments on the epidemiology of the disease. In addition, on-farm and on-station trials have been successfully conducted to show that the following cultural practices are effective in reducing the clump disease.

- **Virus-free seed**. Seed from infected crops should not be used for sowing. This not only has implications for diseases control but also for plant quarantine since *P. graminis* is an ubiquitous parasite.
- **Clean cultivation.** Removal of grassy weeds is crucial for reducing the inoculum and consequently the incidence of the disease.
- **Rotation**. Rotation and intercropping with cereal crops should be avoided. Continuous cropping with dicotyledonous hosts can substantially reduce the disease incidence.
- **Trap cropping with pearl millet**. This is the first time we have demonstrated that a soil borne virus disease can be controlled by using this method. It is inexpensive as well as environmentally friendly.
- **Date of sowing**. Crop cultivated during the postrainy season escape the disease. Even during the rainy season the disease can be controlled by an early sowing and by applying irrigation judiciously.

In conclusion data have been presented to show that peanut clump disease can be controlled by methods which are cost effective and environmentally friendly. We presume they can readily be adopted by a small scale farmer in the semi-arid regions.

Prospects

- Diagnostic tools for the first time have been developed for the detection and quantification of *P. graminis*. These were found to be cost effective and applicable to a large number of field collected samples. Serology with its ability to discriminate between various *P. graminis* isolates could prove a valuable tool in characterization studies. In conjunction with the automatic immersion system (AIS), serology was proved useful in assessing the inoculum potential of the vector in the soil. This will replace the traditional microscopic examination of roots after staining with carcinogenic compounds as phenol. Therefore the method developed is also safe.
- Soil characteristics which are congenial for *P. graminis* survival and multiplication have been determined. As a result geographic information system could be used to locate the potential areas of clump disease occurrence.
- A laboratory method (AIS) has been developed for successfully screening plants for evaluating resistance to clump disease. This will be very valuable in future for identifying sources of resistance in wild *Arachis* sp and for evaluating transgenic resistance.
- In this work we mostly focused on the effect of cultivating post-rainy season crops on the incidence of peanut clump disease in the ensuing rainy season crops. However, studies on the influence of the cropping system practiced during the rainy season are likely to yield valuable clues to a better understanding of the variation in IPCV incidence in rainy season crops of groundnut. The ability of monocotyledonous crops to build up virus inoculum potential can be expected to be high if they are raised during the rainy season, characterized by conducive temperatures and rainfall for the multiplication of *Polymyxa* sp. (Legrève, 1999, Delfosse *et al.*, 1996), as compared to the post-rainy season.
- Sunflower and marigold (*Tagetes patula* L.) are known to possess nematicidal properties. Low virus incidence was observed in a rainy season crop of groundnut after growing marigold in the post-rainy season. The substances produced by the roots of marigold and sunflower may also possibly affect *P. graminis*. Marigold is a valuable cash crop for farmers all over India where it is used extensively for ornamental purposes. Like mustard, marigold may be accepted by the farmers in Rajasthan as a suitable winter crop to replace wheat and barley in clump infested areas.
- The mechanisms that trigger the germination of *P. graminis* resting spores have not been extensively studied. We suspect that as in the case

of striga (*Striga* spp. Lour.) a parasitic flowering plant whose seed has a long viability and is stimulate to germinate by substances exuded from their host plants (Hauck, Müler & Schildknecht, 1992), a similar mechanism regulates *P. graminis* infection of monocotyledonous hosts. It is worth to test the effect of root exudates such as strigol on the germination of *P. graminis* sporosori. This type of investigation may help to identify crops resistant to *P. graminis* infection by not producing stimuli, or crops which produce large quantities of stimuli but do not support the vector multiplication. If these compounds can be synthesised, their application at field level, prior to sow susceptible crops, may lead to reduction of inoculum potential and consequently reduce disease incidence.

- Soil fumigants have been shown to be efficient in controlling clump disease (Reddy et al., 1988). However the use of such chemicals has always been an expensive remedy which could be economically justified only on high value crops. Disquiet about environmental contamination threatens the future use of these chemicals. However as components of an integrated approach to clump disease control, chemicals can have an important function in decreasing numbers of infective propagules of *P. graminis* to levels at which other remedies such as cultural practices may be used to their best advantage. Their use was recommended on research stations to eliminate both the virus and *P. graminis* to avoid the risk of propagating the virus through seed (Reddy *et al*., 1997).

Final comments

This study does not pretend to bring definite answers. It has demonstrated however the great complexity of a viral disease affecting groundnut crops in developing countries. The work was aimed at formulating management practices on the basis of knowledge gained from epidemiological studies. Peanut clump disease is known to occur for more than six decades in the Indian sub-continent and in some of the West African countries. Prior to undertaking this study no cost effective measures were available to control peanut clump. The disease is considered to be a difficult one to deal with because of extremely wide host range of the virus as well as the fungal vector, and the ability of the vector to survive in infested soils for many years.

A set of cultural practices have been proposed which were shown to be effective under limited on-station and on-farm trials. The economic importance of the disease was apparent as a result of the surveys we conducted. In India, scientists as well as farmers were very much encouraged by the cultural methods for controlling this disease obtained with this investigation. Consequently they were successful in obtaining funds from the State government to continue the work on peanut clump with emphasis on farm-tests of the technology found to be effective in this thesis.

This work has humbly laid down bridges over obstacles towards a better understanding of the epidemiology and the development of possible ways to control peanut clump disease. However, it also raised number of new questions and hypothesises. There is now more food for thought for the future generation of young scientists including and ex-nutritionist.

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