CONCLUSIONS AND FUTURE RESEARCH

8.1 CONCLUSIONS

The work presented in this thesis explored the potential of using optical and microwave remote sensing methodology and data for retrieval of biophysical parameters of crops and soil moisture. The various multi-sensor satellites (viz. Sentinel - 1A, ALOS - 2, Sentinel - 2, Landsat – 8, MODIS and PROBA - V) were investigated for robust monitoring of crops and soil moisture in developed or modified algorithms at different frequency and polarizations. The optical and microwave remote sensing technique is basically based on the accurate interpretation of the interaction mechanism of EMR signal with different features of the Earth's surface. Therefore, the SAR backscattering response of different crops and soil moisture depends on (i) frequency, polarization and angle of incidence of the system and (ii) vegetation growth stages, vegetation canopy, leaves orientation, vegetation water content, dielectric constant and the soil surface parameters. Therefore, the modelling of backscattering for precise study of vegetation and soil is equally important to plug-in the both system and surface parameters. Also, the important intention of the developed vegetation and soil algorithms is to reduce the unknown model parameters to avoid the complexity of inversion steps.

The results obtained for the modelling of backscattering for the retrieval of biophysical parameter and soil moisture using multi-sensor satellite data and microwave scattering algorithms led to the following conclusions:

- The combination of SAR and optical satellite data provided better monitoring for the vegetation and soil surface condition than SAR or optical satellite sensors alone.

- The Red - Edge (wavelength interval between Red and NIR spectral region) based vegetation descriptors play significant role in microwave scattering algorithm to improve the forward modelling ($\sigma°$ (dB)) simulation over the vegetation canopies at VV and VH polarizations. Therefore, the $NDVI_{RE}$ index was found high sensitive in the developed algorithm than NDVI, MSR and other optical indices using Sentinel-1A (C -band) satellite data. Also, it may further assess the HH and HV polarizations and different microwave regions (L - and X - bands) for robustness of this Red - Edge vegetation descriptor.
- The f_{veg} parameter in combination with MWCM addressed the important factor to weight the contribution of σ_{veg}^{0} and σ_{soil}^{0} within a pixel at vegetative soil regions and helped the retrieval accuracy of LAI than WCM or older vegetation scattering model at VV and VH polarizations.
- The synergetic form of backscattering model of vegetation (i.e. MWCM) and direct scattering model of soil (i.e. MSSM) were used for the retrieval of LAI over crop using C - band (5.405 GHz) Sentinel - 1A images and Landsat - 8 data. The inverse modeling results indicated a high potential of the proposed modified synergetic algorithms to retrieve LAI more accurately at finer spatio-temporal resolutions than that of well established on-board PROBA - V and MODIS LAI products. Therefore, the developed synergetic of MWCM and MSSM algorithms may provide a new tool for the inversion of biophysical parameters at finer resolution by coupling the recent advances of SAR and optical satellite data.
- The coupling of MTRFR and LUT inversion algorithm were used to enhance the inversion performance of soil scattering model for spatio-temporal mapping and retrieval of soil moisture in the vegetative and sparse vegetative cropland. Hence, the

jointly use of machine learning and LUT approach may significantly solve the ill-posed inversion problems than parametric and iterative optimization algorithms.

- Soil geometrical and physical models have better choice to understand the soil moisture conditions and soil surface parameters than soil parametric regression model using SAR data at different polarizations and frequencies. Because, geometrical and physical models are sensitive with dielectric constant, roughness parameters and moisture level.
- The 2 × 2 covariance scattering matrix (C_2) was generated for the understanding of polarimetric behaviour on the vegetation using ALOS - 2 and Sentinel - 1A SAR satellite data. The DpRVI, PRVI and RVI were computed using both SAR data. The simulated results justified that the DpRVI at HH + HV polarization was found to be more sensitive in high order microwave scattering algorithm than at VV + VH polarization. On the other hand, PRVI and RVI showed comparatively less sensitive in the scattering algorithm.

8.2 FUTURE RESEARCH

The next era of optical and microwave remote sensing satellite will be fine spatial and temporal resolution or multidimensional sensors using airborne and space borne platforms. It is necessary to increase the knowledge of scattering mechanism from the vegetation canopy and soil layers for the development of the higher order of microwave scattering model or algorithms. The following topics will be considered in the future to further improve the microwave scattering algorithms for higher accuracy of monitoring and retrieval of vegetation growth variables and soil surface parameters.

- The fusion of optical and microwave scattering algorithm for the development of the time series fine Spatio - temporal LAI image using multi-sensor satellite data

- Formulation of attenuation impact over a different crop and soil layers using Polarimetric SAR and optical satellite data.
- Hybrid polarimetric study of vegetation (combination of covariance (C_4) and coherency (T_3 and T_4) matrix) using quad-polarization SAR satellite data (ALOS - 2 and RADARSAT - 2)
- Polarimetric interferometric SAR (PolInSAR) and Polarimetric SAR (PolSAR) study for better classification of vegetative crop lands and their scattering mechanism (viz volume, surface, double bounce and other orders of scattering).
- Disaggregation of coarser resolution SMAP soil moisture satellite into fine resolution using physical algorithm and novel radar vegetation fraction.
- Development of the hybrid inversion algorithms (use of machine learning techniques and high computation mathematical model) to improve the retrieval of biophysical and soil parameters from high order physical modelling.
- Development of the detailed theoretical/physical framework to quantify the vegetation scattering effects to increase the potentiality of application of remote sensing in the field of agriculture and hydrology.