Chapter 6

Conclusions and Future Outlook

The overall conclusion from the previously stated research presented in the previous chapters—which mostly addresses the investigation of the relationship between neutrino masses and modern cosmology, including the formation of the universe's baryon asymmetry (BAU)—was covered in this chapter. We have constructed a variety of models within different frameworks of the neutrino mass model. In this thesis, we have given special emphasis on the framework of seesaw models with two right-handed neutrinos and their extension. The frameworks that we have considered are minimal forms of type-I, inverse, and radiative seesaw models. Our focus is on the theoretical origin of neutrino mixing and the viable parameter space for low-scale leptogenesis.

We summarize the key findings derived from our research and outline the potential directions for future exploration and advancement in this field of study in the following sections.

6.1 Conclusions

6.1.1 Chapter 2

In this chapter, we have studied the S_4 symmetric flavor model, which uses a minimal Type-I seesaw mechanism to produce the TM_1 mixing pattern in the leptonic sector. To achieve this, we extended the scalar sector by adding a flavon,

ψ, whose vacuum expectation value satisfies the orthogonality conditions with ϕ_l and ϕ_ν. The resulting effective neutrino mass matrix predicts NH for neutrino masses, with 0.0576 eV $< \sum m_i <$ 0.0599 eV. We calculated an allowed region for the model parameters, which ensures that the predicted mixing angles, CP phase, and mass squared differences fall within the 3σ bounds of current oscillation data. We used chi-squared analysis to determine the best-fit value among various points within the 6-dimensional parameter space. Our analysis shows that the effective Majorana neutrino mass, $|\langle m_{ee}\rangle|$, is relatively small and difficult to detect in $0\nu\beta\beta$ experiments.

We also investigated baryogenesis via flavoured resonant leptogenesis. The right-handed neutrinos are degenerate at the dimension 5 level, and hence a tiny splitting was generated by including a higher dimension term. We took the splitting parameter, $d \simeq 10^{-8}$, and obtained a non-zero, resonantly enhanced CP asymmetry from the out-of-equilibrium decay of right-handed Majorana neutrinos. We solved the Boltzmann equations to analyze the evolution of particles and asymmetry. We considered the best-fit values for the model parameters as inputs and calculated the baryon asymmetry, which was found to be $|\eta_B| \approx 6.3 \times 10^{-10}$.

6.1.2 Chapter 3

In this chapter, we explored the inverse seesaw model ISS(2, 2) with minimal form and S_4 flavour symmetry. This symmetry helps determine the mass matrices and mixing pattern in the leptonic sector. We tested the model by analyzing how well it fits the experimental data using χ^2 analysis. We found that the model describes the experimental neutrino data for NH of neutrino masses with the best-fit value at $\chi^2_{min} \approx 0.24$. However, the model rules out the case of IH of neutrino masses, with $\chi^2_{min} > 100$. The model predicts the Dirac CP phase at the best-fit point to be $\delta_{CP} \approx 370.087°$, which can be tested in future precision experiments. The model also predicts a very small effective Majorana neutrino mass, which cannot be tested in future experiments.

We considered the allowed region for the model parameters by selecting the points in the parameter space that satisfy $\chi^2 \leq 30$. Using this allowed region, we evaluated the effective Majorana neutrino mass and found very small values. Experiments such as T2K and NOνA can help us validate our model by resolving the octant of the mixing angle θ_{23} and providing a precision measurement on Dirac CP-violating phase δ_{CP}.

Finally, we conclude that the constrained parameter space obtained from our model can be used to study low-scale leptogenesis in future work.

6.1.3 Chapter 4

The study explores a radiative seesaw model that addresses the origins of neutrino masses, Baryon Asymmetry of the Universe (BAU), and Dark Matter. The model involves an additional inert Higgs doublet and extends the fermion sector by introducing two nearly degenerate right-handed neutrinos at the TeV scale. The research focuses on resonant leptogenesis, where Z_2 odd right-handed neutrinos decay into Z_2 even Standard Model leptons and an inert Higgs doublet, creating CP-violating conditions out-of-equilibrium. The study considers the quasi-degenerate nature of the right-handed neutrinos and explores leptogenesis at TeV-scale temperature. CP violation necessary for successful leptogenesis is assumed to originate from phases in the neutrino mixing matrix (PMNS matrix). The model favors a Normal Hierarchy (NH) of neutrino masses, with the Dirac phase (δ_{CP}) and Majorana phase ($\alpha = \sigma - \rho$) as key parameters. Numerical solutions to coupled Boltzmann equations reveal a parameter space that successfully generates the observed baryon asymmetry. The best-fit values for δ_{CP} and α are found to be 0.46π and 0.62π, respectively. The study discusses how the requirement for resonant leptogenesis constrains the effective light neutrino mass relevant to neutrinoless double beta decay. The calculation of $|\langle m_{ee}\rangle|$ indicates a significant dependence on both CP phases. Future experiments on neutrinoless double beta decay are identified as potential avenues for exploring and testing this model.

6.1.4 Chapter 5

This chapter explores resonant leptogenesis within the minimal form of the inverse seesaw model ISS(2, 2). The model extends the Standard Model by incorporating two right-handed and two singlet neutrinos. The study focuses on quasi-degenerate, quasi-Dirac sterile neutrino states in the context of resonant leptogenesis. Using the Casas-Ibarra parametrization for the Dirac mass matrix of the ISS(2, 2) model, the analysis investigates viable parameter spaces for resonant leptogenesis. Three scenarios are considered, involving CP violation from both high-energy parameters and low-energy CP phases, exclusive low-energy leptonic CP violation, and the inclusion of a texture zero in the Dirac mass matrix. The study utilizes best-fit values of mixing angles and mass-squared differences as inputs and allows certain parameters to vary. The coupled Boltzmann equation is numerically solved to describe the Lepton asymmetry evolution, ultimately yielding the baryon asymmetry. The model is found to align with experimental data on the Dirac CP phase up to a 1σ confidence level in the normal hierarchy case for all three scenarios, with a specific agreement in the inverted hierarchy case when considering texture zeros in the Dirac mass matrix. The work concludes by noting the potential for future precision experiments to provide more stringent results on the Dirac CP phase and further probe the model.

6.2 Future Outlook

The Standard Model (SM) has some limitations and doesn't give a complete understanding of neutrinos' properties. In this thesis, we explored various models based on the minimal seesaw model and its extensions. We studied the origin of neutrino mixing patterns using the S_4 flavour symmetry in these models. In addition to this, we have focused on the viable parameter space for resonant leptogenesis with special emphasis on the connection between leptogenesis and low-energy CP phases.

Exploring other possibilities within the constructed models presents many opportunities for extending this work. We outline some of these prospects in the following section.

- We can use the modular symmetry to explore the flavor structure of the models considered above.
- It would be interesting to study the implications of TeV scale radiative seesaw models in collider and rare decay experiments.
- Parameter space for leptogenesis in ISS(2, 2) model with hierarchical right-handed neutrinos can be explored in detail.
- More detailed analysis of leptogenesis can be performed by comparing analytical calculations to numerical results of the Boltzmann equation.