10.1 Conclusions

Wastes generated from the different manufacturing processes and energy production units are attributed to environmental and health issues. Instead of landfilling, the waste can be recycled or reused to convert marketable value-added products with high ecologic and economic interest. Furthermore, the safe recycling of industrial by-products or wastes is essential and even vital at present for our society with the growing volume of waste generation. Ceramic industries are attracted particularly in waste recycling perceptions. The recycling of the wastes for the fabrication of ceramics is essential because it consumes a huge amount of natural raw materials. Within this objective of the study, the following important outcome can be drawn:

- Waste RHA is being considered as a renewable and sustainable silica source for ceramics because it contains large quantities of amorphous silica. Without heat-treated RHA and heat-treated RHA contain 90.13 wt.% and 93.20 wt.% of silica, respectively. After the chemical treatment of RHA, the amount of silica is increased above 99 wt.%. The estimated cost of this amorphous nano-silica is approximately 37.3 $ per kg, which is cheaper than the market price of high purity (>99%) nano silica (<50 nm). This silica is capable to produce silica foams with above 70% of open porosity through control compaction at low foaming temperature.

- RHA extracted sol is a good substitute for commercially available colloidal silica and silica sol. 7.5 wt.% silica containing sol with reactive alumina is able to fabricate in-situ mullite foam through the slip-casting method at only 1300°C. The foam specimen is retained ~75.99 % total porosity, ~11.07 MPa compressive strength, and thermal conductivity of ~0.153 W/m·k.

- RHA extracted 30 wt.% silica containing sol is developed for providing sustainable green strength in high alumina refractory castable. This silica is reacted with different alumina sources in the castable at above 1200°C and formed in-situ mullite, which is enhanced the cold and hot strength and BFS corrosion resistance of the castable specimens. Total 5 wt.% silica (2 wt.% dry sol and 3 wt.% from sol) containing sample fired at 1550°C exhibits HMoR around 14 MPa at 1400°C and retains thermal shock resistance (1200°C to room temperature) after 10^{th} cycles ~57 % of its initial strength value. This waste derived sol can also be used in place of colloidal silica, sol-gel derived sol, or fumes silica for the fabrication of cement (CAC) free castable system for high temperature applications like steel ladles and blast furnaces lining.

- Waste RHA and chicken eggshell can be able to produce synthetic wollastonite above 1100°C through an economical solid-state route. β-wollastonite is formed after calcination at 1100°C and at 1200°C, it contains mainly α-wollastonite with a slight portion of unconverted β-wollastonite. The dielectric properties of the wollastonite are not affected significantly by the transformation of β to α phase. The wide range of temperature (30 to 480°C) does also not alter the dielectric behavior of the waste derived wollastonite.

- Wastes derived β-wollastonite, and river silt (Kosi river, India) can be used as ingredients in place of feldspar and quartz, respectively, for the fabrication of ceramic tiles. The physico-mechanical properties of the tile samples are reduced with the incorporation of river silt in place of quartz for low-temperature sintering, but at high-temperature, mechanical properties don't have significant influence through this substitution. The fully replaced quartz and 1130°C fired sample can be used as unglazed ceramic wall tiles. Subsequently, all the properties are improved with wollastonite addition in place of K-feldspar and reduced the sintering temperature at ~30°C. Wollastonite containing 1100°C sintered tile specimens fulfill the main desire properties of the porcelain stoneware tile bodies as per ISO 13006.

- Waste seashell, fly ash, RHA, and RH are able to fabricate ceramic board samples, which can be used in place of conventional calcium silicate board. 1:1 weight ratio of fly ash and heat-treated seashell mixture calcined at 1100°C is retained larnite (Ca_2SiO_4) and calcium aluminate ($Ca_3Al_2O_6$) as major phases. This ceramic powder with RHA, RH, and OPC is capable to produce ceramic board (CB) specimens at room temperature through the casting process. The CB specimens are demonstrated a lower density, low thermal conductivity, and good mechanical strength, which are good matching with the technical data of the calcium silicate board manufacturing company.

- The sustainable insulation refractory samples are successfully prepared using fly ash, RHA, RH, and fired refractory grog. The thermal conductivity and bulk density of the specimens are reduced with the incorporation of wastes. 95 wt.% waste containing sample fired at 800°C can be envisaged as an insulation refractory.

Consequently, silica and mullite foam, cement free high alumina castable refractory, synthetic wollastonite, tile, ceramic board, and insulation refractory can be fabricated through sustainable and ecological routes using wastes like RHA, eggshell, seashell, fly ash, Kosi river silt, and refractory grog. Moreover, sustainable fabrication of ceramics not only helps the ceramic industry but also saves the environment and society from the pollution.

10.2 Future scopes

The valorization of the wastes and up-grading as a substitute for primary natural resources can present numerous benefits for societies. Ceramic industries may start the consumption of wastes, and then both problems, i.e., disposal of wastes and crisis of natural resources, may be solved. However, industrially produced ceramics from waste ingredients are not yet widely maturated. Therefore, the more deep investigation is required in technological transfer from the academic to the industry for commercialization the waste-derived ceramics. The technology transfer is becoming a confrontation from different perspectives, like ethics, knowledge, and risks of unsustainability. Therefore, more encouragement is required for industrial manufacture for recycling the wastes. As far as wastes incorporation in the composition of the ceramics is concerned, the following objectives can be investigated for further growth and advancements of the waste recycling in ceramics:

- The optimization is required for large scale production of nano silica, silica sol, and synthetic wollastonite from RHA.
- More investigations are required about the RHA derived silica and sol for the fabrication of other materials like coating and ceramic paints.
- A comparative study with commercially available colloidal silica sol to waste RHA derived sol in no cement castable is required.
- The investigation about different process parameters like firing temperature with changing of the chemical composition of wastes is essential for the commercialization of the ceramic board and silt containing tiles.
- Explorations of other ceramic products with solid wastes may be considered.