EMERGING CHALLENGES AND OPPORTUNITIES IN NR TECHNOLOGY

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Natural rubber possesses certain unique properties such as elasticity, resilience, toughness, impermeability and non-conductivity. It is the combination of these useful properties in a single material that has led to the use of rubber as the main raw material in over 50,000 products and articles, influencing the quality of human life in different ways. The earliest reported use of rubber was for makingthe 'bouncing balls' used by the Mesoamerican people for the 'ball game' (Schidrowitz, 1952). The scientific observations on the novel properties of the crude natural rubber,brought by the European explorers,resulted in the early innovations on the applications of this new material in areas such as waterproofed garments, footwear *etc*. Thus the impetus for the early research attempts in rubber technology was from the 'supply push', trying to find new applications for the crude material available from wild sources. With the development of automobiles and the pneumatic tyre, demand for rubber increased considerably and the supply from wild sources had to be augmented by raising rubber plantations in different parts of the world, particularly in South East Asian countries. Also, some of the shortcomings of the material, particularly its tendency to become sticky at high ambient temperature and brittle at low temperature and also its inadequate strength properties were the main reasons for the discovery of perhaps the most important innovations in rubber, *viz*., vulcanization and the practice of its reinforcement with filler (Kauffman, 1989). Such 'demand pulls' were the main driving force for the second major phase of innovations in rubber. Today, rubber has been transformed from a mere material of curiosity to one of the most important industrial raw materials, driving the wheels of world economy, thanks to the systematic scientific innovations made world over right through the last three centuries.

Like any other sector of the industry, rubber industry also has been facing a

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number of challenges. Apart from supply chain constraints and relatively high raw material prices, the physical and chemical limitations of the raw polymerand the consequent constraints in processing andalso environmental issues caused by the rubber industry pose great challenges, management of which is vital for the very survival of the industry and the world at large. This paper is therefore, an attempt to oversee the present and future research priorities in rubber technology, so as to ensure sustained growth of the industry in the years ahead. For the sake of convenience, the paper is divided into different sections covering the various sectors of the rubber industry from primary processing to latex technology.

Primary processing

Primary processing of NR involves conversion of the fresh latex and other forms of crude rubber collected from plantations into convenient forms, suitable for storage, marketing and further processing into finished products (Semegen and Cheong, 1978). The major forms of primarily processed NR include ribbed smoked sheet(RSS), technically specified rubber (TSR), crepe rubbers and preserved and concentrated latex.

Ribbed smoked sheet rubber

The earliest form of processed NR, RSS, is still being produced in certain countries such as Thailand, India and Sri Lanka, accounting for about 21 per cent of NR production. The preference for this form is mainly on account of socio-economic considerations. The relatively high energy cost in drying and the variability in quality owing to the small batch size and the stock holding practices of growers remain as the majorshortcomings. While group processing can minimize quality variations, cost of drying has to be reduced by using improved smoke houses and by using alternative energy sources such as solar, biogas *etc*. The attempts already made in countries such as India and Sri Lanka have to be pursued vigorously. Viscosity stabilisation of sheet rubber can be arrived at a minimum cost and this can offset the effect of long-term storage of sheet and will be of great advantage to the consuming industry. Even in individual small holdings, the effluent generated from sheet rubberprocessing can lead to pollution problems (Jean Le Bras, 1957). Hence, the practice introduced in India for using the effluent as input for biogas generation and using the gas for drying of sheet, reduces the overall cost of drying while improving the green image of NR. With the reduced availability and higher cost of labour for tapping and other social factors such as part-time and absentee farming, more and more growers are likely to dispose of the crop as latex and hence, availability of RSS in future and its preference by the consuming industry, can be ensured by organizing group processing as well as by introducing new innovations such as the above.

Technically specified rubber

While competition from synthetic rubbers was the main reason for the introduction of TSR in the mid 1960s, other factors such as reduced availability of labourand increased wages in Malaysia and the relatively inferior quality and presentation of RSS and crepe rubber also contributed to the growth of TSR production and today around 60 per cent of global NR production is processed as TSR. The various advantages of TSR such as guaranteed and uniform quality with known technical parameters, better presentation and relatively lower price have been appealing to the consuming industry, particularly the tyre sector, most of which have introduced modern quality management systems, which require standardized raw materials of consistent and guaranteed quality.

Variation in the quality of the raw material used for TSR and the protocol followed in different countries for their collection and transportation appears to be a major problem affecting the quality of the processed rubber. In spite of the advances already made, this problem remains to be addressed further. In India, only the leftover field coagulum materials, collected and handled by different means and stored for varying periods, is the major part of the raw material used. Themolecular degradation undergone by this material and the inconsistency in its quality parameters pose great challenges to the TSR processor in making a rubber of satisfactory quality. This is a problem which needs to be addressed urgently and the efforts already made in India in treating the field coagulum to prevent its putrefaction during storage, shall be continued to improve the quality of TSR. This will also minimise the odour problem prevailing in TSR processing units. The possibility of collecting and transporting fresh field coagulum to processing units, may be another alternative to improve quality of TSR.

With the reduced availability and higher cost of labour and also because of part-time and absentee farming, the increased availability of fresh field latex at lower price in countries such as India, has opened up new opportunities for using latex grade raw material for TSR production. This is also likely to minimise the unhealthy competition and hence the price of the available field coagulum material in the raw material market. Another emerging possibility is the higher capacity utilization in the existing TSR factories, which have been suffering from lower capacity utilization and hence higher processing cost. However, use of latex grade material in TSR production, calls for changes in the effluent treatment systems used in TSR factories. Partial processing of the fresh field coagulum and latex in the latex collection centre itself, as has been practiced in Indonesia, can be considered which might also help in decentralizing the effluent treatment system (Nguyen and Luong, 2012). In the decentralized units, the available effluent can be treated more advantageously by establishing biogas plants.

Preserved and concentrated latex

The unique strength properties of NR, makes it the ideal raw material for the production of a large variety of latex based products.Hence, over 10 per cent of the rubber produced is marketed as preserved and concentrated latex. NR latex being a natural product, it contains a large number of non-rubber constituents including carbohydrates and proteins, making it a good medium for the growth of microorganisms such as bacteria and yeast, leading to spontaneous coagulation and putrefaction. Hence, preservation against bacterial attack is essential to keep the latex stable and ammonia has been traditionally used for the purpose (Johnson, 1853). Even today ammonia is the most preferred preservative in spite of certain obvious disadvantages. Alternatives already developed are not found as good as ammonia. However, the search for alternative preservatives has to continue as there are situations where use of ammonia may not be advisable.

Concentration of the latex by raising its rubber content from the normal value of around 33 per cent to over 60 per cent is essential for making latex product manufacturing processes technically and economically viable (Blackley, 1997). Centrifuging is the most widely practiced method, although creaming also has been employed at a limited level. Not much developments have been made in these processes over the last many decades. Some of the shortcomings in the centrifugal process such as frequent stoppage of the machine owing to sludge build-up, larger proportion of rubber going into the skim *etc*. need some attention. Alternative processes such as ultra-filtration shall be tried, particularly in the case of modified forms of latex such as epoxidised latex. A fresh look at the existing specification parameters used for assessing the quality of the concentrated latex is considered desirable, as those parameters alone may not suggest the suitability of the latex for certain processes.

Crepe rubbers

Crepe rubber processed from field coagulum is no more attractive on account of its relatively poor quality and presentation and hence has been phased out in many of the producing countries. The limited quantities of this form of rubber produced in other countries shall also be phased out and the existing units may be converted as TSR processing units or the facilities may be more meaningfully used for processing latex and fresh field coagulum in the collection centres (Kurian and Mathew, 2011).

Pale latex crepe (PLC), made from fresh field latex under controlled conditions, still commands a premium and hence production of this form of rubber is still considered viable. Sri Lanka is the leading producer of PLC and the related form, sole crepe. The predominance of certain clones such as PB86, yielding fairly white latex, was the primary reason for the popularity of this form of processing in Sri Lanka. Although those clones have been replaced with others, even now this traditional system of processing is being continued in that country for commercial reasons. As a number of new high yielding clones are widely planted in most rubber producing countries, a fresh attempt to identify clones more suitable for PLC (as also other forms such as low viscosity grades of NR) production is considered relevant.

Modified forms of NR

While natural rubber possesses many unique properties, making it suitable for general purpose applications such as tyres, it has certain limitations caused by its chemical structure. At the same time, as the polymer has already been biologically synthesized in the tree, those limitations cannot be overcome by modifying the synthetic pathway, as is done in the case of man-made polymers. Hence, the only alternative to modify the properties of NR is to modify the same through physical or chemical processes. Considerable work has been done in this field in many laboratories and a few modified forms of NR are already available in the market (Elliott, 1979).

In the physical route of modification, blending with other polymers is an area where further work is desirable, as new polymers and modified polymers are introduced and also to improve further the properties of blends already developed (Kurian and Mathew, 2011). Another potential area is readymade compounds or masterbatches which result in significant improvement in properties. In the area of chemical modification, focus shall be on introducing desired functionality to the polymer. This might help in improving the compatibility of NR with polar ingredients like silica and other polymers. In order to make any significant impact in the tyre industry, it is necessary that such modification processes have to be simple and economical. It is pertinent to observe that the preference for solution SBR in rubber compounds used in 'green tyre' is owing to the presence of pendant vinyl groups in SSBR, making it more compatible with silica.

It is pertinent to point out that considerable activities have been in progress in USA and European Union to develop alternative sources of NR such as guayule rubber. The production of bioisoprene rubber is also being attempted. Compared to *Hevea* tree, breeding for higher yield and desirable characteristics of rubber is likely to be easier in shrubs like guayule. Similarly modern techniques such as genetic transformation of such smaller plants are likely to be easier than in *Hevea*. Hence, the possibility of producing NR with a more desirable molecular arrangement from sources like guayule is not very remote. Therefore, while research in similar lines on Hevea shall be pursued more vigorously, simultaneous efforts are desirable to make modified NR with novel properties as indicated earlier.

Automotive tyre industry

Natural rubber is perhaps the most important raw material for the tyre industry. Its high strength properties, high adhesion to steel cord, low hysteresis loss and hence low heat build-up, high flexibility at low temperature and excellent tack and green strength are some of the important reasons for its large scale use in tyre production. More than 60 per cent of the global production of NR is used by the tyre industry and hence, research on NR technology will become meaningful, only if it addresses the requirements of this sector. For this purpose it is desirable to appreciate the current trends in the tyre industry and their possible impact on NR. Some the trends in tyre technology are discussed here.

Tyre rolling resistance

Over 65 per cent of the fuel consumption by a vehicle is wasted as heat and of the remaining 35 per cent used for propulsion, around 25 per cent is required for overcoming rolling resistance for car tyres and over 10 per cent for truck tyres. The contribution of the rubber compounds used in tyres to the overall rolling resistance is fairly well known. After the introduction of silica as reinforcing filler in tyre compounds in the early 1990s, about 50% reduction in the rolling resistance of passenger car tyres has been achieved which is roughly equivalent to 10 per cent fuel saving. This remarkable breakthrough has been achieved through a combination of the use of the right polymer, easily dispersible silica grades, appropriate coupling agents and by modifying the rubber mixing technology.Unlike carbon black, silica is a strongly polar material and hence does not disperse well or interact with the non-polar rubber, unless a chemical bond is established between the two phases. This has been achieved through the use of bifunctionalsilane coupling agents and modification of the mixing technology comprising precise temperature control, longer time and provision for de-volatilisation of the reaction product, ethanol, from the mix.

The chemical reactivity the rubber with the coupling agent plays a key role in achieving good reinforcement with silica (Wolf, 1987). Presence of pendant functional groups in the polymer makes it more reactive with the coupling agent. This is the main reason for SSBR being used in 'green tyre' compounds. Highly non-polar NR with no pendent vinyl group is not considered suitable for silica reinforced tyre compounds. Hence, attempts to modify NR, to raise its chemical functionality, are necessary for the rubber to make any inroads into this area. There are already reports about epoxidised NR being more suitable for silica reinforcement. However, grafting of bifunctional chemical entities on NR through an economically attractive process is likely to be more rewarding. NR, being a natural product, if modified to make it more compatibile with silica, is likely to be a better candidate than its synthetic counterparts, as raw material for fuel saving car tyres of the future.

'Tyre magic triangle'

While trying to reduce rolling resistance, tyre makers come across reduced wet grip as well as shorter tread life. In order to ensure satisfactory performance on the road,allthe conflicting requirements that a tyre has to deliver will have to be maintained. Working within this magic triangle and achieving all the three mutually conflicting performance requirements, is the real challenge to the scientist (Alexander, 2009). It is fortunate that silica reinforcement of tyre compounds is helpful, to some extent, in achieving this goal. Then the other aspects of tyre compounding, processing techniques as well as tyre design play important roles.

'Green tyre'

Green tyre is an environmentally friendly tyrewhich has several benefits over normal tyres including better safety, particularly on wet and icy roads and reduced fuel consumption. The rubber compounds for green tyre contains ingredients such as treated silica, instead of carbon black, and other environmentally friendly raw materials. Use of a renewable and natural raw material like *Hevea* rubber can make the tyre still greener. However, the lower breaking efficiency of NR based tyre tread compounds is a constraint, which can be managed, to a certain extent, through silica reinforcement.

Tyre labelling

This again is aimed at protecting the environment from the adverse impact of the road transportation industry. From November 2012 onwards, in the environment conscious European Union, it will become mandatory that all tyres produced after July 2012, will have to display labelling information with a grading based on rolling resistance, noise and wet grip. Gradually they will also have to comply with minimum performance requirements. The objective is to make tyre performance more transparent, as otherwise it is difficult for the customer to differentiate. Simultaneously, it is expected to reduce CO_2

emission through lower rolling resistance without compromising safety.

All the above developments in the tyre industry offers more challenges and at the same time certain opportunities for natural rubber.

Use of carbon black in tyre compounds

For a high performing product like tyre, reinforcement of the rubber with ahighly reinforcing filler like carbon black still remains unavoidable in spite of its fossil origin and the increased use of non-fossil based materials like silica. However, achievement of the full reinforcing potential of black in tyre compounds is limited by factors such as dispersion, especially in the case of the most renforcing grades of black such as ISAF and SAF. New processing techniques are being considered for improving this. The recent development of NR latex stage carbon black masterbatch is a step in the right direction (Tangboriboonrat and Rakdee, 2001). However, refinement of the process, particularly with respect to dispersion, rubber-filler interaction, process loss *etc*. are considered necessary before it can be commercialized.

Nano and fibrous materials in tyre compounds

Rubber based nanocomposites are a class of organic-inorganic hybrid materials, where the inorganic part is uniformly distributed at nano-scale within the polymer matrix (Zou*et al*., 2008). The materials used for this include nanoclays, silica, expanded graphite, carbon nanotubes, nanofibres. Mechanical, dynamic mechanical and tribological properties of natural rubber/ nanofiller/carbon black nanocomposites exhibited synergistic improvements within the 'tyre magic triangle' offering low rolling resistance, improved wet grip and better wear properties (Rubber Technologist's Handbook, Volume 2, 2009). Also, some of these nano materials are reported to impart good thermal and barrier properties to the rubber. Most of these improvements are brought about at fairly low loadings. However, further work is necessary to improve dispersion of these materials in the rubber matrix and other issues related to processing of the mixes as well as to minimise possible health risks associated with the use of some of these materials. Moreover, it is time that the laboratory scale work already done in this field has to be taken to the next logical step of making commercially viable products. The potential application of these composites will help natural rubber in making further inroads into the tyre field.

Use of short fibres as reinforcing agents in rubber is not a recent development. In spite of the advantages of high modulus and tear resistance, the concept did not take off for various reasons such as processing issues. However, new materials such as short aramid fibres are now reported to confer increased abrasion resistance and low strainmodulus, better puncture resistance and higher green strength (Biron, 2007). Perhaps, a fresh look on this subject, particularly with new materials, is likely to be rewarding.

Tyre retreading

Used tyres have become a source of great environmental concern, particularly in the developed countries. While retreading of used tyres has been widely recognized as an economically and environmentally acceptable practice, a large volume of used tyres, suitable for retreading, are still discarded (Boustani*et al*., 2010).

While the technology of conventional retreading has evolved over a long period, that of the pre-cured or 'cold process' of retreading is a fairly recent introduction and since then the quality of retreading has improved significantly. However, much more needs to be done, particularly with respect to standardization of the process followed in the unorganized sector. While most of the consumers of retreaded tyres such as fleet owners, look only for durability of the new tread, other aspects like fuel efficiency, riding comfort, wet grip, noise level, bonding with the casing are also to be factored in. Standardization with respect to such factors is necessary, especially in emerging economies such as India and China.

General rubber goods industry

Around 40 per cent of the available NR is used in the general rubber goods industry. Hence, the developments in this sector are also considered significant in shaping the fortunes of NR. Moreover, a considerable part of this sector is in the unorganized sector, which is not capable of undertaking and significant R&D work on its own. At the same time, sustained research support is needed for this sector, considering the wide range of products manufactured.With the lifting of most of the trade barriers, the rubber industry in the developing countries has been facing severe international competition and the very survival of the sector depends on its capacity to improve competitiveness of its products in terms of both quality and cost. This calls for product oriented R&D support for the industry. This can best be done through joint efforts between the industry and academic and R&D institutions. Some of the areas which need focussed attention are discussed below.

NR in civil engineering applications

The uniqueproperties of NR in terms of strength, fatigue, creep, durability and elasticity make it the material of choice in many civil engineering applications (Yura*et al*., 2001). Considerable work in this field have already been reported and products such as bridge bearings, seismic bearings, rubber shock cells for offshore oil platforms, inflatable rubber dams have demonstrated the suitability of NR for such demanding applications. Further work in this area, to be taken up in a multidisciplinary manner, will be rewarding.

Automotive rubber components

With the rapidly growing demand for automobiles in emerging economies like China, India and Brazil, the demand for high quality non-tyrerubber components has been going up. The technical requirements for such products for the present day and future generations of automobiles will be highly demanding (Woo *et al*., 2006). Development of such products calls for considerable R&D work, to be carried out jointly with the OE and component manufacturers.

Rubber products for military applications

A large number of rubber products find their way into military equipment and facilities. Many of these items need periodic replacement even during peace time. The technical requirements of these products vary much depending upon the type of equipment or environment where they are used. Natural rubber and its blends with other polymers can be the raw material for many of such applications, provided adequate R&D work are undertaken jointly with the appropriate military and industrial establishments.

Impact of new regulations such as REACH

With the introduction of REACH regulations in the European Union in June 2007, export of rubber products to EU countries is possible only by complying with the regulations. Although, at present only a limited number of rubber chemicals have been included in the candidate list of substances of very high concern (SVHC), more and more items are likely to be added to the list in the years to come. Moreover, in future such regulations are likely to be introduced in other countries/regions. Hence, in order to sustain the growth of export of rubber products, it is necessary to find out alternatives to the restricted chemical substances. Some successful attempts have already been reported with respect to aromatic process oil, which is already included in the list of SVHC.This has to be a continuous effort, and identifying cost-effective alternatives is a challenging task, which can best be done jointly with manufacturers of chemicals and other ingredients.

Fire retardant products

Being a hydrocarbon polymer, NR is inflammable. At the same time fire retardancy is one of the important requirements for rubber products used in automobiles, rail coaches, aircraft, oil installations and public places such as hospitals (Babrauskas*et al*., 1988). However, this aspect is very often than not, is overlooked resulting in loss of lives in fire accidents. Earlier work in this area focussed on the use of fire-retardant ingredients such as halogen compounds. Restrictions on the use of organo-halogen compounds opens up the area for further attempts to impart fire retardant properties to NR based products. The recent observation that nano-fillers such as nanoclays impart fire retardant properties to NR may have to be pursued vigorously in order to achieve this objective.

Reclamation process and applications of reclaimed rubber

As most of the rubber products are vulcanised, reprocessing of used and waste rubber products is not as easy in the case of thermoplastics based products. This has been one of the serious disadvantages of rubber, resulting in the accumulation of large of volumes of used rubber products including tyres, causing great environmental issues in many parts of the world, particularly in developed countries. While reclamation of rubber present in such waste materials has been practised for a long time, this industry is more popular only in developing countries, mostly on account of economic pressure. Also, the quality of reclaimed rubber obtained through the popular processes is far inferior to that of the new rubber, restricting the application of reclaimed rubber in bulk quantities, only in low value products. Hence, development of new processes for reclaiming rubber, ensuring the quality of the reclaim, is necessary particularly in view of the anticipated shortage of NR in future and for minimising the environmental risks of having 'used tyre mountains'. The delink process evolved by B.C Sekhar had the advantage that a product manufacturer could reclaim waste from his own process, thereby ensuring the composition of the compound remains relatively unchanged

(Hon *et al*., 1995). More radical approaches including biological routes may have to be explored. Although national and international standards are available for reclaimed rubber, these are not being followed widely, resulting reclaimed rubber of highly varying quality, causing processing and quality issues for the products manufactured from it.

Use of reclaimed rubber is considered mostly as a means of achieving economy. However, there are certain advantages such as better mixing and extrusion behaviour, which are very often overlooked. If the rubber compound containing reclaimed rubber is properly designed and processed, this form of rubber can be used advantageously even at higher proportions in selected products. Such products are to be identified and compounding and processing methods evolved to be transferred to manufacturers in the small and medium sectors.

Latex technology

Globally over 10 per cent of the NR is consumed by the latex products manufacturing sector. With the high strength properties coupled with relatively low modulus and high wet gel strength, NR latex has been the preferred choice for a wide range of products, from rubber bands to meteorological balloons (Mathew, 2001). The formulations and processing techniques used for latex productsare quite different from those employed for dry rubber based products. In spite of the advances in synthetic latices and arguments against NR latex owing to problems such as protein allergy, it dominates the market even today. However, some of the issues which require due consideration in order to sustain the dominant market share of NR latex are discussed below.

Protein allergy and related issues

Out of the 1-1.5 per cent of proteins naturally present in NR latex, a major portion is removed during the process of concentration by centrifuging. However, a portion of the proteins associated with the rubber phase along with a small quantity remaining in the serum pass on to the final product, causing certain allergic reactions to people who are sensitive to such proteins. Although NR latex based products have been used for many decades, allergic issues gained prominence only during mid-1980s when use of latex gloves and condoms increased in large volumes owing to the spread of serious diseases such as AIDS. The problem necessitated measures to reduce such adverse reactions which included change over to gloves made from alternative materials such as nitrile rubber and PVC. This caused serious concerns to NR producers who started working on measures to minimise the problem. Removal of proteins from latex through processes such as double centrifuging and enzyme treatment, resulted in the production of deproteinised latex (Cherian and Jayachandran, 2009). Also, the processes of manufacture of dipped goods like gloves and condoms have been refined by introducing leaching, halogenation, polymer coating *etc.* with significant reduction in the extractable protein content. Moreover, standards and test methods have been evolved with the broad objective of making NR latex products acceptable to healthcare professionals and other consumers. In spite of all these developments, small amounts of proteins are still found in latex products which might become a point of contention particularly in view of the fact that alternative materials including natural rubber from sources other than *Hevea*, are being introduced into the market. Hence, the efforts on removal of allergenic proteins and other materials from latex products may have to be continued.

Chemically modified NR latex

Use of modified forms of NR latex in the manufacture of latex products have not been attempted seriously yet, though dry forms modified NR have found many applications. The only exception is perhaps the pre-vulcanised latex which is commercially being used. Even in this case alternative techniques of vulcanisation such as that using irradiation did not make much headway, although it has the definite advantage of being free from chemicals. Latex from styrene and methylmethacrylate based graft copolymers of NR have been reported to yield films with higher modulus and tear strength. The potential use of such latex in products like moulded foam with higher compression modulus, or elastic thread with higher tensile modulus *etc*. could be explored (Bogner, 2008). Also the use of deproteinised latex and the techniques of protein removal from latex products have potential application in items like electricians' gloves. The absence of a suitable method of concentration of epoxidised latex is the main constraint in extending the application of this modified form of NR in latex products. As in the case of dry forms of NR, possibilities for novel forms of modified latex also shall be explored, so that latex products with special properties could be developed.

Nanofillers in latex compounds

As in the case of tyres and other dry rubber based products, nanofillers are reported to have potential applications in latex based products. One of the serious disadvantages of latex products is the inability to be reinforced with particulate fillers. The low energy mixing process in latex is unable to cause production of rubber free radicals, formation of which is necessary for reinforcement with particulate fillers. It is here that nanofillers become relevant and even at relatively small loadings, nanofillers are reported to impart reasonable level of reinforcement to the rubber (Mathew *et al*., 2007). In addition to strength, other properties including barrier properties and ageing resistance are also improved. What is more important now is to consolidate the findings already made and to develop specific products with defined properties, which otherwise are not possible in the conventional manner.

CONCLUSION

The above attempt was only to point out some of the current and evolving issues in NR technology and the possible opportunities ahead. However, all those observations may not be relevant from a practical point of view, but might be helpful in planning for future work in this field. In order to realise the objectives in the desired manner, it is necessary that further work is taken up jointly with other centres of excellence and also with the user industry. Such collaboration is likely to help in identifying clear targets and in taking up work in a more time-bound and result-oriented manner.

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