Wound Healing Activity of Ethanolic Extract of *Selaginella Bryopteris* on Rats

Shravan Kumar Paswan¹,²,*, Sajal Srivastava², ChandanaVenkateswara Rao¹

**ABSTRACT**

The objective of the present study was to determine wound healing activity of ethanolic extract of *Selaginella bryopteris* on rats. The whole plant of *S. bryopteris* Linn. was collected from Andhra Pradesh, India and extraction was done using ethanol. GC-MS analysis was performed to determine active metabolites present in the extract followed by determination of total phenolic and flavonoid contents. *In vivo* wound healing activity of ethanolic extract was evaluated using excision wound model. The extract was applied topically on animals by preparing ointment in two concentrations (5% and 10%) where soframycin (10%) was taken as positive control. Antioxidant activity of *S. bryopteris* extract was observed by measuring oxidative enzymatic levels i.e. Superoxide dismutase (SOD), Catalase (CAT), reduced Glutathione (GSH) and lipid peroxidation (LPO) in animal tissues. Histopathological studies of excised skin were carried out after the experimental period. The contraction rate of the wound was higher and dose-dependent in rats treated with 5% and 10 % ointment of extract in comparison to untreated control group. The drug treated groups showed recovery phase and the percentage of healing was more in 10% at the end of experimental period. Results exhibited sufficient insights on the healing process with normal recovery stages and restored oxidative enzymatic levels. Histopathological findings provided additional positive results; the dermis with proliferating capillaries and skeletal muscle were replaced by cellular fibrous tissue and collagen fibers. Overall, the results showed that ethanolic extract of *S. bryopteris* was an interesting traditional agent that possess significant wound healing activity.

**Key words:** *Selaginellabryopteris*, Total Phenolic Content, Flavonoid Content, Oxidative Stress, Wound Excision Model.

**INTRODUCTION**

Wound can be defined as an injury of living tissue or damage in the epithelial integrity of the upper layer of skin, which may further lead to disturbance in skin anatomy, physiology and their function.¹ Wounds are the major cause of morbidity and mortality throughout the world. Wound is the result of accidental damage, which may be susceptible to bacterial and other pathogens that provides an entry point for systemic infections.² Chronic wounds affects the quality of life especially in older adult population.³ Wound healing is a systematic process leading to the restoration of injured tissues.⁴ It can be described as regeneration of the injured connective tissue of wounds followed by proliferation and migration of dermal and epidermal cells, and matrix synthesis.⁵ Healing of wounds depends on factors such as repairing ability of the tissue, type and extent of damage and general state of the health of the tissue.⁶ However, wound healing drugs are still unsatisfactory due to their high cost, low availability, and various side effects.⁷ Medicinal plants have been used in the treatments of several diseases and such traditional medicines are still widely practiced today.⁸ Therefore, herbal medicine would be useful as therapeutic or even in the prevention of chronic wounds due to common belief that they are safe, reliable, clinically effective, low cost and better tolerated by patients.⁹

*Selaginellabryopteris* Linn. Bak is commonly known as 'Sanjeevan'. The Indian tribal communities mainly use it as a strength tonic in improving fitness and to extend lifespan¹⁰ and used as a major ingredient in local pills for the treatment of patient with spermatorrhoea, venereal diseases, constipation, colitis, indigestion and urinary problems (diuretic). It is also treat patients who are unconscious, and to lower the body temperature in patient with fever.¹¹,¹² All parts of this plant are considered to be a good source of large number of bioactive substances. The important natural compounds in this plant are characteristic flavonoid-dimers, bioflavonoids.¹³ Earlier phytochemical analysis of *S. bryopteris* showed the presence of 2,3-dihydrohinokiflavone, tetrahydro-hinokiflavon, 2,3-dihydroamento flavone, lanaroflavone, sciadopitysin, sequoiaflavone, hinokiflavone, 2’, 3’-dihydroamento flavone and tetra-o-methyl-hinokiflavone.¹⁴ The herb also possesses chemo-preventive and anti-carcinogenic property¹⁵ anti-stress,¹⁶ memory enhancement,¹⁷ anti-diabetic activity,¹⁸ anti-depressant activity¹⁹ and antimicrobial.²⁰ Many plants are used in tribal and folklore medicine across many countries for the treatment of wound and burns. These natural agents induce healing and regeneration of the lost tissue by multiple mechanisms. The presence of various life-sustaining constituents or potential bioactive principle(s) in plants has urged scientific community to understand the nature of the compounds.
to examine these plants for their potential wound healing properties.\textsuperscript{13} Therefore, the findings in this study could provide baseline information and accumulating evidence suggest that ethanolic extract of \textit{S. bryopteris} have an effective wound healing and antioxidant activities by promoting the cellular proliferation, migration of fibroblast cells and restoration of oxidative enzymes. In the present study we investigated the effects of \textit{S. bryopteris} extract in excision wound healing model and presents data that warrants further clinical studies.

**MATERIALS AND METHODS**

**Chemicals and reagents**

Soframycin, Soft paraffin, Cetostearyl alcohol, Polysorbate 60, Butylated hydroxy anisole, Formalin, Xylene, Hematoxylin, Eosin Polypyrrole cags were purchased from Sigma Chemical Co. USA and from Indian firms.

**Plant material and extraction of metabolites**

The whole plant of \textit{S. bryopteris} Linn. was collected from Andhra Pradesh, India and authenticated by K. Madhava Chetty, Venkateswara University, Tirupati, India. The voucher specimen (voucher no. 1098) was deposited in the institute. The collected plant material was dried at room temperature and powdered using grinder then 100 g of powdered material was weighed and allowed to dipin 70% ethanol for 48 h. The extraction of metabolites was carried out till the transparent color was obtained. The ethanolic extract was collected and concentrated through vacuum in evaporator Christ RCV 2-18 plus. The concentrated extract was stored at 20°C for the further analysis.

**GC-MS analysis**

The non-targeted qualitative and quantitative analysis of ethanolic extract was performed through Gas Chromatography-Mass Spectrometry (GC-MS) with three replicates. For the GC-MS analysis of the metabolites, a volatile trimethylsil (TMS) derivative of the sample was prepared. Sample (5 mg) was dissolved in 50 μL of methoxyamine hydrochloride solution in pyridine (20 mg/mL). The mixture was shaken for 2 hr at 40°C using thermomixer comfort (Eppendorf India Ltd.). After this 70 μL of N-Methyl-N-(trimethylsil) trifluoroacetamide (MSTFA) was added followed by shaking for another 30 min at 40°C. GC-MS analysis was performed using Thermo Trace GC Ultra coupled with Thermo Fisher DSQ II mass spectrometers. Chromatographic separations of metabolites were carried out using thermo TR50 column (polysiloxane column coated with 50% methyl and 50% phenyl groups). Xcalibur software was used to process the chromatographic and mass spectrometer data. The oven temperature of GC was maintained at 70°C for 5 min, then gradually raised at the rate of 5°C min\textsuperscript{-1}; 70°C to 310°C with 5 min for the sample. The mixture was injected in the split mode (splitting ratio of 1:16). Helium was used as a carrier gas and set at a constant flow rate of 1 mL min\textsuperscript{-1}. The mass selective detector was run in the electron impact (EI) mode, with electron energy of 70 eV and mass range between 50-800 amu. The characterization of individual metabolites was carried out using WILLY and NIST mass spectral library.\textsuperscript{21}

**Assay of total phenolic contents**

The amount of total phenolic content of ethanolic extract of \textit{S. bryopteris} was determined according to Folin-Ciocalteu procedure and the content was expressed as gallic acid equivalents (GAE) in mg/g of extract. In this method, \textit{S. bryopteris} extract (200 μL of 1 mg/mL) was mixed with Folin-Ciocalteu (0.5 mL) for 3 min. In this mixture, 2 mL of sodium carbonate (20%, w/v) was added then the mixture was placed in dark condition and absorbance measured at 550 nm.\textsuperscript{22}

**Assay of total flavonoid contents**

Total flavonoids were also estimated according to aluminum chloride colorimetric method. In this method, \textit{S. bryopteris} extract (50 μL of 1 mg/mL) was mixed distilled water (4 mL) and NaNO\textsubscript{2} solution (5% of 0.3 mL) followed by addition of 10% AlCl\textsubscript{3} solution after 5 min incubation. This mixture was stand for 6 min followed by addition of 1 mol/L NaOH solution and final volume was make up with distilled water (10 mL). The absorbance was measure at 420 nm. A yellow color indicated the presence of flavonoids. Total flavonoid contents were calculated as rutin (mg/g).\textsuperscript{22}

**In vivo wound healing activity**

**Experimental animals**

Wistar rats weighing between 180-200 g with no prior treatment were used for the study. Animals were housed in polypropylene cages maintained at 22 ± 2°C temperature with 12 h light and 12 h dark cycle. The animals were fed on a standard pelleted diet and had free access to water throughout the experiment. Animals that are described as fasting were deprived of food for at least 16 h but allowed free access to drinking water. The animals study was approved by the Institutional Animal Ethics Committee, CSIR-National Botanical Research Institute (Approval No. 1732/GO/RE/CPCEA), Lucknow, as stated by prescribed guidelines of Committee for the Purpose of Control and Supervision of Experiments on Animals (CPCSEA), Government of India.

**Preparation of ointments**

Ointments of ethanolic extract of \textit{S. bryopteris}in two concentration of 5% and 10 % (w/w) were prepared by mixing 5 and 10 mg of extract, respectively and each with soft paraffin (25 mg), glycerin (12 mg), polysorbate 60 (5 mg), cetostearyl alcohol (4 mg) andbutylated hydroxyl anisole (0.02 mg).[23]

**Experimental design**

A total of 24 rats were divided into four groups each containing six rats with identical wounds. Group – 1 was control group containing untreated rats; Group – 2 and 3 were treated groups containing 5% and 10% prepared ointments, respectively; Group – 4 was positive control group containing standard drug Soframycin.

**Excision wound model**

Excision wound was made on the depilated region of the skin. A standardized wound area (8 mm\textsuperscript{2}) was marked on the dorsal surface of the anaesthetized rats and skin in full thickness was excised to obtain a wound area of about 8 mm\textsuperscript{2}. Homeostasis was attained by blotting the ulcerated area with cotton swab dipped in normal saline. The wound diameter was measured using calipers on alternate days and the epithelization period recorded at the end of the study.\textsuperscript{15} Number of days required for falling of the eschar without any residual raw wound gave the period of epithelization. It was measured in days from wounding day (day zero) till the full Epithelization. The wound area was measured with a translucent paper and traced on every 3\textsuperscript{rd} day. The contraction of wound was expressed as percentage of the reduction in wound size. Percentage of wound contraction was measured using the formula given below.

\[
\text{Percentage of Wound contraction = } \left( \frac{\text{Initial wound area} - \text{Specific day wound area}}{\text{Initial wound area}} \right) \times 100
\]

**Antioxidant activity**

Antioxidant activity was determined by measuring oxidative stress enzymes in wound tissue homogenate i.e. Superoxide dismutase (SOD),...
Catalase (CAT), reduced Glutathione (GSH) and lipid peroxidation (LPO) were estimated after day 12 post wounding. Tissue homogenate was prepared by excision of wound tissue using the same punch (8 mm² diameter), which excised wounded area without contaminating it with normal skin then tissue was collected in Phosphate buffered saline (PBS, pH 7) and sample preparation was done according to Shaik et al. SOD activity was analyzed and expressed in μmoles/min/mg of protein according to the method of Kakkar et al. Colour intensity of the chromomar was measured at 560 nm. For determination of CAT enzyme level, 900 mg tissue was homogenized in 3.0 ml M/150 phosphate buffer in ice and centrifuged at 30,000 rpm for 1 h at 4°C. The supernatant was taken to determine catalase activity. For determination of GSH level tissue homogenate (30% w/v) was prepared in 0.15 M Tris-HCl buffer (pH 7.4) then trichloroacetic acid was added to precipitate proteins. Samples were centrifuged at 15000 rpm at 4°C for 1 h. The supernatant was analyzed for contents of reduced glutathione and expressed in terms of μg/g of liver tissue. Lipid peroxidation assay was performed by taking tissue homogenate in 3.0 ml 0.15 M Tris-HCl buffer (pH 7.4) and centrifuged at 3000 rpm at 4°C for 1 h. The supernatant was collected and estimated for lipid peroxidation which was expressed in expressed as nmol per mg of proteins.

**Histopathological study**

Skin tissues were dipped into 10% formalin solution and preserved for 24 h at 4°C. These tissues were dehydrated using alcohol and then embedded in paraffin wax at 58 - 60°C. Thin sectioning of the skin tissues (5-7 μm) were fixed onto a slide and stained with haematoxylin, and later counterstained with eosin [16].

**Statistical analyses**

Statistical analyses were performed using GraphPad Prism (GraphPad Software, Inc.). One-way ANOVA followed by t-test was used to analyses the significance in wound contraction rate. Two-way ANOVA followed by Bonferroni post-hoc test was used for testing groups with different time points with respect to percentage of wound healing. *P< 0.05; **P< 0.01; ***P< 0.001 were considered statistically significant. Data are expressed as mean ± SD.

**RESULTS**

**GC-MS analysis**

GC-MS analysis of hydroethanolic extract of *S. bryopteris* exhibited presence of sugar, sugar alcohol, glucosides steroids, Saturated and unsaturated fatty acids and vitamin as shown in Figure 1. The relative concentration of major compounds were Sucrose (27.95%), maltose (16.31%), oleic acid (9.25%), palmitic acid (6.01%), glucopyranosides (13.40%) and glycerol (3.39%). Several other compounds were also exhibited in *S. bryopteris* extract as shown in Table 1.

**Assay of total phenolic and flavonoid contents**

Total phenolic content was expressed as mg gallic acid equivalent per gram extract dry weight. Phenolic content of the extract was calculated and the value was found to be 364.2 ± 1.92 mg/g. Similarly, total flavonoid content was expressed as mg rutin equivalent per gram extract dry weight and value was found to be 50.30 ± 2.01 mg/g.

**Excision wound model**

Application of *S. bryopteris* ointment on marked area showed significant wound healing activity when compared to control group. Rats showed normal healing process with signs of improvement at weekly intervals and this was determined by their contraction rate as shown in Table 1. A dose dependent effect was observed in rats treated with ointment. These groups showed faster wound contraction when compared to normal and positive control group. On day 14, 5% ointment treated group showed 52.66% wound contraction while 61% wound healing activity was observed at 10% ointment, which was higher than standard drug soframycin (56%) as shown Figure 2. The mean time taken for complete epithelialization of the excision wound in 10% ointment treated group was less in comparison to positive control group (Figure 3). However, untreated control group animals showed very less improvement in the contraction rate with less than 50% as the wound was visible on day 28. Whereas, rats treated with ethanolic extract and soframycin showed full recovery at the end of the day 28.

**Histopathological changes of skin in rats**

Histopathology of skin showed improvement in the acute wound healing process with normal architecture, granulation tissue formation having fibroblasts and inflammatory cells in untreated control group animals. The deep vascular layer of the skin showed proliferative tissues consisting of lymphocytes, collagen fibers and blood vessels (Figure 4A). The rats treated with 5% ointment exhibited dermal fibrosis with collagen fibers. The wound is covered with one or more layers of cells and there is renewal of the dermis with proliferating capillaries and more neovascularization. The dermis and skeletal muscle has been replaced by cellular fibrous tissue and collagen fibers (Figure 4C). Positive control showed focal ulceration.

**Table 1: Compounds present in GC-MS analysis of *S. bryopteris* extract.**

<table>
<thead>
<tr>
<th>Rt</th>
<th>Metabolites</th>
<th>Chemical formula</th>
<th>Relative concentration(%)</th>
<th>Class of compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2</td>
<td>Glycerol</td>
<td>C12H2O3Si</td>
<td>3.39</td>
<td>Polyol</td>
</tr>
<tr>
<td>25</td>
<td>Glucitol</td>
<td>C24H62O6Si6</td>
<td>1.3</td>
<td>Sugar alcohol</td>
</tr>
<tr>
<td>25.34</td>
<td>Glucose</td>
<td>C22H55NO6Si5</td>
<td>1.12</td>
<td>Sugar</td>
</tr>
<tr>
<td>30.6</td>
<td>Palmitic acid</td>
<td>C19H4O2Si</td>
<td>6.01</td>
<td>Saturated fatty acid</td>
</tr>
<tr>
<td>34.17</td>
<td>Oleic acid</td>
<td>C21H42O2Si</td>
<td>9.25</td>
<td>Unsaturated fatty acid</td>
</tr>
<tr>
<td>37.29</td>
<td>Glucopyranoside</td>
<td>C36H86O11Si8</td>
<td>13.4</td>
<td>Glucosides</td>
</tr>
<tr>
<td>37.59</td>
<td>Turanose</td>
<td>C33H78O11Si7</td>
<td>1.86</td>
<td>Sugar</td>
</tr>
<tr>
<td>38.79</td>
<td>Sucrose</td>
<td>C36H86O11Si8</td>
<td>27.95</td>
<td>Sugar</td>
</tr>
<tr>
<td>39.71</td>
<td>Maltose</td>
<td>C26H86O11Si8</td>
<td>16.31</td>
<td>Sugar</td>
</tr>
<tr>
<td>46.23</td>
<td>Tocopherol</td>
<td>C31H56O2Si</td>
<td>0.44</td>
<td>Vitamin</td>
</tr>
<tr>
<td>48.07</td>
<td>Cholesterol</td>
<td>C30H54O5Si</td>
<td>0.41</td>
<td>Steroid</td>
</tr>
<tr>
<td>49.41</td>
<td>Campesterol</td>
<td>C31H56O5Si</td>
<td>0.74</td>
<td>Steroid</td>
</tr>
<tr>
<td>49.76</td>
<td>Stigmasterol</td>
<td>C32H56O5Si</td>
<td>1.14</td>
<td>Steroid</td>
</tr>
<tr>
<td>50.62</td>
<td>β-Sitosterol</td>
<td>C32H58O5Si</td>
<td>1.34</td>
<td>Steroid</td>
</tr>
</tbody>
</table>
and replacement of skeletal muscle along with the capillaries. The wound was covered by the epithelium consisting of one or more layers of cells (Figure 4D).

Photomicrograph of sections of skin from rats with H & E skin microscopic image of (A) Untreated control group (B) *S. Bryopteris* extract ointment (5% w/w), (C) *S. Bryopteris* extract ointment (10 % w/w), and (D) Soframycin (10% w/w) treated group.

**Antioxidant activity of *S. bryopteris* extract**

Treatment with extract of *S. bryopteris* was significantly restored antioxidant enzymatic levels in the rats. SOD, CAT and GSH in wound tissues were significantly increased in the case of rats treated with 10% (26.0 nmol/mg, 0.8 IU/mg and 180.2 μmol/mg, respectively) and 5% (26.8 nmol/mg, 0.8 IU/mg and 175.9 μmol/mg, respectively) w/w ointment in the excision wound model in comparison to the untreated control group animals (22.1 nmol/mg, 0.5 IU/mg and 49.2 μmol/mg) as shown in Table 2. However, LPO level was reduced with the treatment of plant extract i.e. 4.3 nmol/mg and 2.9 nmol/mg for 5% and 10%, respectively compared to control group (7.3 nmol/mg). The enzymatic levels of soframycin treated group was near to extract treated group. The values were 25.9 nmol/mg, 0.7 IU/mg, 209.0 μmol/mg and 1.7 nmol/mg for SOD, CAT, GSH and LPO, respectively (Table 2).

**DISCUSSION**

The antimicrobial results obtained from our previous work further provides supporting information on the wound healing properties of ethanolic extract, of *S. bryopteris*. We evaluated the wound healing process by measuring the progressive contraction size of the wound. Wound contraction, a process that occurs throughout the healing process, commencing in the fibroblastic stage (area of the wound undergoes shrinkage), enters a proliferative phase, characterized by inflammation, angiogenesis, collagen deposition, granulation tissue formation and epithelialization finally leads to wound contraction resulting in a smaller amount of apparent scar tissue. Inflammation, the preliminary part of the wound healing process plays a significant role in the removal of infective microorganisms. In the absence of effective treatment, however, inflammation may be prolonged and the microbial load may increase. Thus, the bacterial load and the endotoxins may lead to the prolonged elevation of pro-inflammatory cytokines and the wound may enter a chronic state and fail to heal due to the prolonged inflammatory phase. The results of the present study showed significant acceleration of the wound healing process in animals treated with 10%ethanolic extract of *S.bryopteris* (Table 3), which could be due to the shortened inflammatory phase and antimicrobial effect of the bioactive compound. Our results are in agreement with other...
Figure 4: Histopathology of skin excised from rats treated with extract of S. Bryopteris.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Wound contraction (mm²)</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>CTRL</td>
<td>8.41 ± 0.30</td>
<td>7.37 ± 0.21</td>
</tr>
<tr>
<td>SBE (5% w/w)</td>
<td>8.74 ± 0.37a</td>
<td>7.14 ± 0.30b</td>
</tr>
<tr>
<td>SBE (10% w/w)</td>
<td>8.53 ± 0.40b</td>
<td>6.29 ± 0.23b</td>
</tr>
<tr>
<td>Soframycin (10% w/w)</td>
<td>8.67 ± 0.37c</td>
<td>5.98 ± 0.30b</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SEM; n=6, One Way ANOVA followed by Student-Newman-Keuls t-test; significantly different at a: *P<0.05*; b: *P<0.01*; c: *P<0.001*, respectively.

Table 3: Antioxidant activity of S. bryopteris ointment on the uninfected excised wound in rats.

<table>
<thead>
<tr>
<th>Oral treatment (mg/kg, od×10 day)</th>
<th>GSH (nmol/mg)</th>
<th>SOD (IU/mg)</th>
<th>CAT (μmol/mg)</th>
<th>LPO (nmol/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>22.1 ± 1.09</td>
<td>0.5 ± 0.09</td>
<td>49.2 ± 1.96</td>
<td>7.3 ± 0.42</td>
</tr>
<tr>
<td>SBE (5% w/w)</td>
<td>26.8 ± 1.55b</td>
<td>0.8 ± 0.06b</td>
<td>175.9 ± 0.4c</td>
<td>4.3 ± 0.22b</td>
</tr>
<tr>
<td>SBE (10% w/w)</td>
<td>26.0 ± 1.07c</td>
<td>0.8 ± 0.07b</td>
<td>180.2 ± 0.52c</td>
<td>2.9 ± 0.35c</td>
</tr>
<tr>
<td>Soframycin (10% w/w)</td>
<td>25.9 ± 0.89c</td>
<td>0.7 ± 0.09a</td>
<td>209.0 ± 0.70c</td>
<td>1.7 ± 0.19c</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SEM (n=6), One Way ANOVA followed by Student-Newman-Keuls t-test; significantly different at a: *P<0.05*; b: *P<0.01*; c: *P<0.001*, respectively.
COMPETING INTERESTS

The author(s) declare that they have no competing interests.

FUNDING


ACKNOWLEDGEMENT

The authors are thankful to our Honorable Director, CSIR-NBRI, Lucknow, for their assistance and providing laboratory facilities. I am so much thankful to my colleague Mrs. Pritt Verma (SRF) and Satish Chandra Gupta for their constant support during the experiment and animal work. Further, we extend our gratitude to University Grant CommissionRGNSRF, New Delhi, India, for providing a grant to perform this study.

REFERENCES

ABOUT AUTHORS

Shravan Kumar Paswan, M.Pharm (Pharmacology), is working as a Senior Research Fellow in the department of pharmacology, CSIR-National Botanical Research Institute. Presently, his research focus on the mechanism of wound healing from traditional medicinal plants, with special interest in various In-vitro and In-vivo activity. His interest also spans the preclinical toxicity studies, Anti-inflammatory activity, Hepatoprotective activity, Reproductive toxicity studies.

Dr. Sajal Srivastava, is a Deputy Director and Associate Professor at the Amity Institute of Pharmacy, Amity University, Lucknow. His research focus on Synthesis of Heterocyclic Compounds, Extraction and biological Screening of natural products, Toxicity study and nasal formulations.

Dr. Ch. V. Rao, currently working as a Senior Principal Scientist and Head, Department of Pharmacology, CSIR-National Botanical Research Institute, Lucknow. He is instrumental in setting up of pharmacology laboratory in NBRI, devoted to botanical herbal drug development, safety and efficacy studies. Dr. Rao published 130 research papers in peer reviewed national and international journals. To his credit he is holding 35 patents and numbers of products were commercialized.