Littoral drift sources and sinks along the Indian coast

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Numerous theoretical and field studies have been carried out to quantify the volume and direction of littoral sediment transport along the Indian coast. Nevertheless, very little effort has been made to identify the sources for the littoral transport, which feed to the nearshore transport mechanism and on sinks, wherein the continuous movement of the littoral sediment breaks and deposits over a considerable period of time. Rivers are the major source for the littoral drift and the annual discharge of sediments to sea along the Indian coast is about 1.2×10^{12} kg. The construction of inland dams, irrigation barrages, have considerably reduced the sediment load brought to the sea. Due to the fall in the influx of sediments and concentration of wave energy, many coastal segments experience erosion. In order to identify the extent of the significance of the major sinks for the sediment deposition along the Indian coast, a study was undertaken to evaluate the long-term sediment deposition in Gulf of Kachchh, Gulf of Khambhat, Gulf of Mannar, Palk Bay and Sandheads. The study shows an average yearly deposition of sediments to a thickness of 0.025 m at Gulf of Kachchh, 0.03 m at Gulf of Khambhat, 0.01 m at Gulf of Mannar, 0.006 m at Palk Bay and 0.003 m at Sandheads. The depositional features identified in the present study have been noticed as occurrences of spits, shoals and the progradation of coastline.

INDIA has an extensive coastline of about 7500 km and the physical regime of the Indian shoreline is characterized by vivid forms like headlands, promontories, rocky shores, sandy spits, barrier beaches, open beaches, embayments, estuaries, inlets, bays, marshy land and offshore islands. The coastal geomorphological processes are influenced by a number of environmental factors, primarily due to geological, meteorological and oceanographical factors which vary from one sector of the coast to another. Any attempt to handle the coastal problems, either to arrest erosion or prevent deposition, requires a thorough understanding of the factors and processes involved in the coastal geomorphological system: the pattern of changes, the sources for the sediments supplied to the littoral region, the sinks acting as large-scale depository basin of the sediments and the volume and direction of sediment movement in the littoral zones.

The primary source of the sediments deposited on the beaches is the weathering of land; the sediments are then transported through rivers to the ocean. The contribution of shelf erosion to suspended sediments in the ocean is unknown and appear to be of a very low order. More than one-third of the world's fluvial sediment load is carried by about a dozen major rivers, wherein the Ganges and Yellow rivers alone contribute 20 per cent of the total[1]. Holeman[2] estimated a global river discharge of suspended solids to the order of 18×10^{12} kg into the ocean every year. The quantities of materials contributed by headland erosion and aeolian transport are both less than 2 per cent of river transport. Another main source of sand for a particular region can be of an eroding upcoast cliff and/or beach. Beaches supply sand when the wave and longshore current transport capacity at a point exceeds the supply of sand from updrift sources to the point. Beach erosion occurs at an increased rate during storms.

Many coastal sinks are ephemeral in nature, only acting to store sediment for a short geological span before it moves further downslope. The time span for which the sediment remains in a coastal sink varies from only a few minutes or hours in the case of some tidal beaches, to several million years in the case of coastal rock formations. In many areas, sand is transported short or for a distance alongshore from its source or sources before being deposited at one or more semi-permanent locations known as sinks[3]. Harbour, bay and estuary with tide-generated reversing flow can trap large volumes of the sediment transported alongshore. The flood tide drives the sediment through the inlet, where it is deposited in quiet water. The ebb tide may carry sand far enough offshore to be effectively removed from the littoral zone. Sand may also be trapped adjacent to jetties constructed to stabilize the entrance channel. Lagoons and estuaries act as long-term sediment sinks for marine sand. Wind might cause a net seaward transport of sand from the dunes to the littoral zone but at most locations, sand is blown predominantly to the dune field from the beach.

Rivers appear as the major sources of sediment for the beach deposits on the Indian coast. The single largest source of sediment for the Arabian Sea is the river Indus[4]. It discharges about 0.45×10^{12} kg of sediment annually, resulting over a course of time in the formation of Indus cone with as much as 2500 m of unconsolidated sediment at its proximal end[5]. There are 14 major rivers, 44 medium rivers and more than 200 minor rivers along the Indian coast, which are acting as predominant sources for the littoral drift. The annual discharge of sediments through these rivers into the sea is about 1.2×10^{12} kg, which accounts roughly 10 per cent of the global sediment flux to the world ocean[6]. The major and medium rivers of India are shown in Figure 1. The average annual runoff

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from the major, medium and minor rivers of India is 1406×10^9 m^3, 112×10^9 m^3 and 127×10^9 m^3, respectively[7]. Based on studies from 1958 to 1962, Coleman[8] has estimated that the combined peak discharge for Ganges and Brahmaputra rivers averages about 91,200 m^3/s, while the lowest averages about 7600 m^3/s. The Central Water Commission has measured and estimated the sediment load carried by important rivers in India. Based on their estimation for the year 1984, the sediment load discharged into the sea is presented in Table 1. Next to rivers, the headlands and beach erosion contribute significantly as sources along the Indian coast. In addition to this, direct runoff and rainfall contribute to the loss of sediments as rainwash from sub-aerial portion of the beach. Another minor loss is due to the mining of beaches for sand and placer deposits.

Although tidal marshes are dominantly composed of silt and clay, sand may be common in the channels draining the marshes and hence, the marsh acts as a sink. The deposition over the beach face and the subsequent aeolian inland transport forming as large, high dunes are the major sink phenomena observed along the Indian coast, particularly along the coasts of Saurashtra, Konkan, South Tamil Nadu and Orissa. Also the lagoons, estuaries, beach storage, sand spits, siltation at harbour channels and formation of marshy lands act as main sinks for the sediments.

The sand spit which is migrating towards north at the mouth of the Chilka Lake is a unique formation of this region. The northerly drift forming as growing spit at the mouth, the formation of shoals and spits inside the lake are the major sinks of this region[9,10]. The long sand bar formed at Kakinada, north of the Godavari river mouth, traps the northerly littoral drift and feeds for the growth of the spit[9,11]. Vembanad lake is one of the major sinks along the Kerala coast. A number of tributaries are

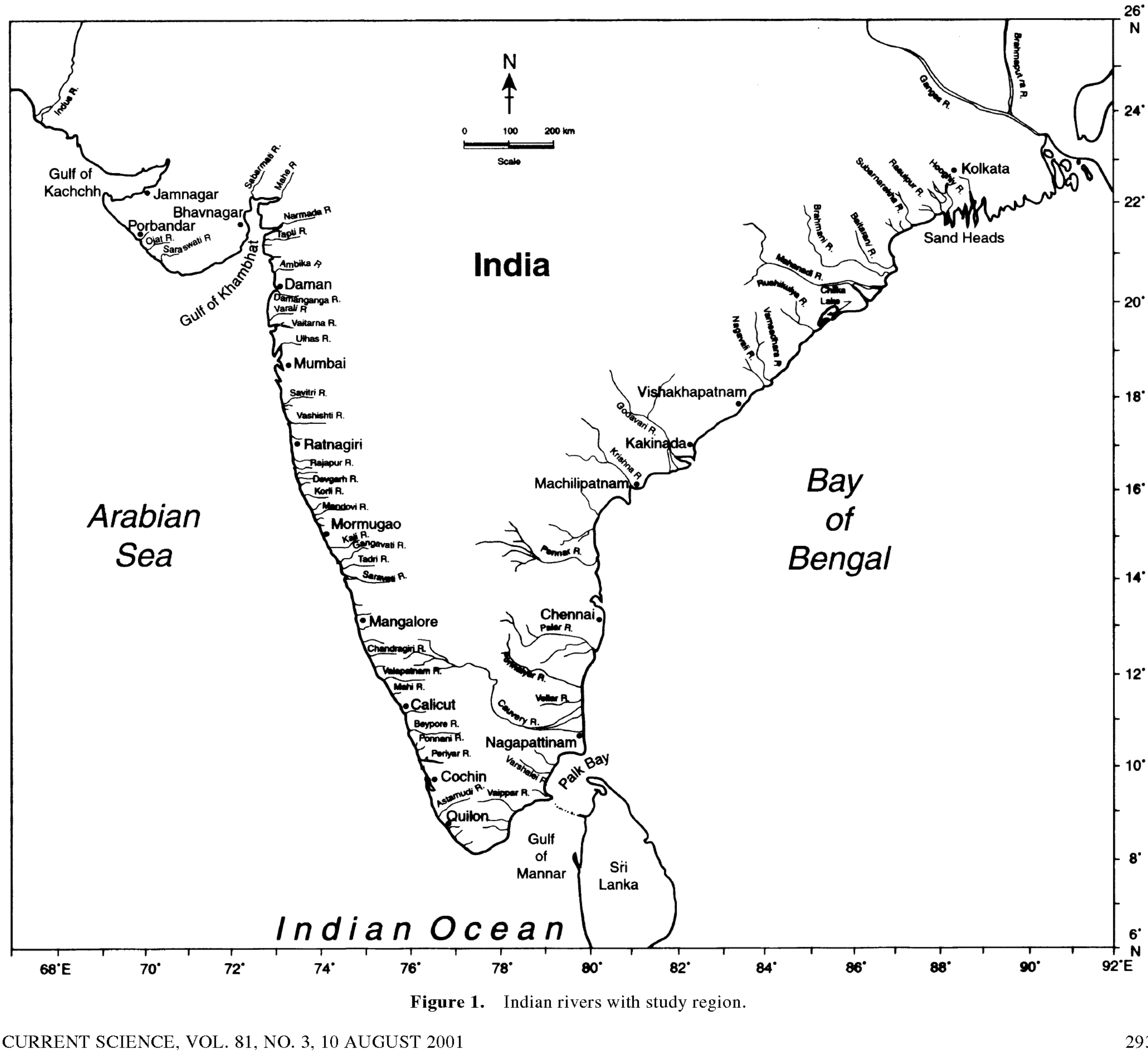

Figure 1. Indian rivers with study region.

present in this region and dump the littoral materials in the lake. Six major rivers, Periyar, Pamba, Manimala, Achankovil, Meenachil and Muvattupuzha discharge into this lake[9,12].

The sediments carried by the rivers and by the surf zone currents as littoral drift get partly deposited in permanent, semi-permanent and temporary sinks along the Indian coast. The Gulf of Kachchh, Gulf of Khambhat, Gulf of Mannar, Palk Bay and Sandheads act as major sinks. In order to identify the extent of their significance for the sediment deposition, a study was undertaken to evaluate the long-term sediment deposition in the above regions.

The naval hydrographic charts corresponding to two different time periods were selected for comparison. The areas considered for estimation of deposition and the details of time span are shown in Table 2. The selected areas were digitized by 1500 m × 1500 m grid for Gulf of Kachchh; 1420 m × 1420 m in 1934 and 1640 m × 1640 m in 1979 for Gulf of Khambhat; 314 m × 314 m in 1906 and 375 m × 375 m in 1981 for Gulf of Mannar; 3000 m × 3000 m for Sandhead areas. The water depth, d, was noted at each grid point and the volume of sand, V, deposited with reference to an arbitrary datum was calculated using

Table 1. Annual sediment load by Indian rivers at terminal points in 1984

River	Sediment load ($\times 10^9$ kg)
Brahmaputra	597.000
Indus	450.000
Ganga	329.000
Narmada	44.358
Godavari	38.839
Brahmani	13.277
Mahanadi	13.204
Tapti	10.522
Baitarni	5.954
Subarnarekha	5.911
Mahi	5.879
Vamsadhara	1.836
Netravathy	1.223
Chellar	0.613
Cauvery	0.471
Bharatpuzha	0.444
Bhadar	0.354
Banas	0.322
Krishna	0.320
Pennar	0.257
Purna	0.238
Periyar	0.199
Muvattupuzha	0.157
Gundlakamma	0.064
Kallada	0.058
Vamanapuram	0.053
Shatrunji	0.041
Achenkovil	0.036
Sabarmati	0.018
Tambraparni	0.011

$$V = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij}\, y_{ij}\,(h_{ij} - d_{ij}), \qquad (1)$$

where x_{ij} is the spacing between the grids in the x-direction; y_{ij} is the spacing between the grids in the y-direction; h_{ij} is the depth of the arbitrary datum; d_{ij} is the depth of the seabed; n is the number of grid points in the x-direction and m is the number of grid points in the y-direction.

The Gulf of Kachchh is a large tidal water body having the water-spread area of 7325 km^2 situated along the north-west coast of India. It is about 170 km long and 75 km wide at the mouth, which narrows down to 18 km near Kandara shoal[13]. The detailed geomorphology, sedimentological parameters and shallow sub-bottom features of the gulf were described by various investigators[14–19]. Presence of several shoals, channels, creeks, inlets and Islands in the Gulf of Kachchh encourages sinking of sediments.

Based on (1), the estimated volume of sediment deposited over the time-span considered is shown in Table 2. The present study in the Gulf of Kachchh covering the area of 138 km × 82.5 km, shows that 0.3×10^{10} m^3 sediment got deposited over a period of 22 years. The estimation further shows that between the years 1956 and 1978, the sediment accumulation on seabed has caused a reduction in water depth of about 0.54 m, i.e. 0.025 m per year.

The results of the present study showing the accumulation of sediment deposition in the Gulf of Kachchh are supported by the formation of a number of mud reefs seen off Okha Rann, off Roji Bet and off Vadinar, near Patre creek. Due to the high tidal range and currents, the upper creek system gets erosion and the sediment brought into the gulf gets deposited as sand shoals, mud flats and sand islands in this region. Pattanshetti *et al.*[13] have stated that Hansthal creek is in depositional feature. The earlier studies[19] showed that at Kandla, Sara, Aanu, Ohang and Chach creeks and the Little Gulf of Kachchh, erosion is dominant and originally evenly-deposited sediments have been modified to a rugged topography by cutting through the sub-bottom reflectors. The migration of the sand waves from Kandla creek to the outer gulf suggests the movement of material from the creeks to the outer gulf. The process of deposition has been further intensified by the presence of the shoals, as flows from the creeks further reduce their velocity due to frictional drag applied by the shoals. The diversification of the currents by the shoals also contributed to the deposition. All these factors helped to create the depositional environment in the outer Gulf of Kachchh.

A major part of the Gulf of Khambhat is moderately indented with deep estuarine inlets of the Arabian Sea[20]. This region is also occupied by various mud flats and sand banks. Sand banks and mud flats are largely occupied in the northern and eastern sides of the gulf, near Sabarmati, Mahe, Dhadhar, Kim and Tapti river mouths.

Rivers Ambika, Purna, Kim, Tapti, Narmada, Mahe and Sabarmati together form an estuarine complex in such a way that the tidal action of the Arabian Sea inhibits the deltaic accumulation of the riverine sediments at their mouths, prohibiting progradation of deltas into the Arabian Sea. Mal Bank is expanding day by day due to the deposition of littoral materials carried by different rivers and creek systems of this region. Except Malcolms channel, the northern part of the gulf is found to be very shallow.

The estimation using eq. (1) covering an area of 130 km × 86 km at the Gulf of Khambhat shows that 0.53×10^{10} m^3 of sediment got deposited over a period of 45 years. Assuming that the rate of deposition is uniform over the years, it is found that between the years 1934 and 1979, the deposition has caused a reduction in water depth of 1.36 m, i.e. 0.03 m per year (Table 2). According to the results of the present study, the muddy estuarine islands (known as bets) at the mouths of Ambika, Purna, Tapti, Narmada, Mahe and Sabarmati are observed to be in depositional trend[20]. During the south-west monsoon, the combined effect of the rivers in spate, the large tidal action with less of wave energy and enhanced discharge of finer sediments by the major rivers help in rapid deposition of mud flats. The earlier study[20] showed that the accretionary tendency of the mud flats towards the land engulfing the older terraces/flats is evident in the area and the average rate of lateral accretion was estimated as 100 m/year.

Along the Gulf of Mannar, the sea–land boundary is almost uniform and regular but for inundation in a few places, where it is intercepted by rivers forming tidal inlets. Tambraparni, Vembar and Vaipar and some other inlets are present in this region. At present, Vembar river is not supplying sediments into the sea, except during the rainy days in the north-east monsoon period. Wave action is low during most of the time and hence, the formation of sand dune is common in this region.

The estimation using (1) covering an area of 19.5 km × 13.5 km at the Gulf of Mannar, shows that 0.02×10^{10} m^3 sediment got deposited over a period of 75 years. Assuming that the rate of deposition is uniform over the years, it is found that the deposition between years 1906 and 1981 has caused a reduction in water depth of about 0.72 m, i.e. 0.010 m per year (Table 2). There are a number of coral banks and islands present in the Gulf of Mannar[21]. Formation of sandy islands off Tuticorin region shows as sinks having accumulation of sand. Large beach storage of sands between Manapad and Tiruchendur, Vembar and Valinokkam and along Rameswaram island indicates depositional features of the littoral sediments.

Vaigai, Vaishali and Valryar rivers and the littoral transport by various sources from the northern part of the Tamil Nadu coast are the major sediment sources entering the Palk Bay region[22]. It is largely occupied by sand banks, numerous shoals, sand spits and islands. Occurrence of cyclonic storm during north-east monsoon is common in the Nagapattinam–Poompuhar region, which causes an erosion along this region. The sediments are transported southerly and deposited in the Palk Bay. Low wave action inside the bay and protection from the southerly waves encourages the deposition of sediment.

In the present study, the estimation based on eq. (1) covering the area of 117 km × 105 km, shows that 0.3×10^{10} m^3 sediment got deposited over a period of 51 years. Assuming that the rate of accumulation is uniform over the years, it is estimated that between the years 1931 and 1982, the sediment deposition has caused a reduction in water depth of about 0.32 m, i.e. 0.006 m per year (Table 2). The depositional feature observed in the present study agrees with the formation of very shallow areas in the Palk Bay. The enlargement of the Manamelkudi sand spit and the emergence of sand banks between Point Calimere and Point Pedro (Sri Lanka) across the entrance of the Palk Bay are the evidences of the depositional features occurring in this region. Usha and Subramanian[23] stated that the accretion pattern was observed in the Palk Bay at Ammapattinam, Mandapam and Rameswaram. Loveson *et al.*[24] have discussed that large amounts of sediments from the pediments are removed constantly by rainfall and carried by minor rivers and dumped into the Palk Bay.

Ganges and Brahmaputra rivers are the major sediment sources in the Sandhead region. The twenty distributaries of the Ganges–Brahmaputra river system represent an relatively flat, low-lying area[25]. Part of this region located on the west represents an abandoned delta which is covered mostly by a thick mangrove forest known as the Sundarbans.

Table 2. Details of time span and area considered for estimation of sediment deposition with estimated volume of sediment deposition and average deposition

Location	Time span (years)	Region considered		Area (km^2)	Volume of sediment deposition ($\times 10^{10}$ m^3)	Average depth of accumulation (m)	Average depth of accumulation per year (m)
		Latitude	Longitude				
Gulf of Kachchh	22 (1956–1978)	22°15′–23°00′N	68°55′–70°15′E	11,385	0.30	0.54	0.025
Gulf of Khambhat	45 1934–1979)	20°55′–22°15′N	72°00′–72°50′E	11,180	0.53	1.36	0.030
Gulf of Mannar	75 (1906–1981)	09°05′–09°15′N	79°05′–79°15′E	261	0.02	0.72	0.001
Palk Bay	51 (1931–1982)	09°17′–10°15′N	78°55′–80°00′E	12,285	0.30	0.32	0.006
Sandheads	104 (1878–1982)	20°55′–21°50′N	87°50′–89°05′E	13,433	0.30	0.30	0.003

The estimation based on eq. (1) considered for the area of 101 km × 133 km at Sandheads, shows that 0.3×10^{10} m^3 sediment got deposited over a period of 104 years. Assuming that the rate of deposition is uniform over the years, it is found that between the years 1878 and 1982, the sediment deposition has caused a reduction in water depth of about 0.3 m, i.e. 0.003 m per year (Table 2). The number of islands and sand shoals present in this region confirms the depositional features identified by the present study. Based on the satellite and seabed data, Barua *et al.*[25] stated that the transport of river sediment is largely restricted to an area landward of about the 20 m isobath during the low-discharge period. It indicated that the nearshore of this region experiences deposition and in the offshore region beyond 100 m isobath, there was no significant change. Based on the year-by-year investigation at Hooghly estuary from 1854 to 1956, Hiranandani and Ghotankar[26] reported that the sediment brought by the river discharges slowly form as shoal patches and subsequently develop as small islands. Due to ebb drift, the shallow patch north of mud point tends to join the shallow tail of the Haldia sand. From the 1904–1905 and 1909–1910 surveys, they stated that at the outfall of Haldia river, the channel had a unusual sink and is a depositional trend. Based on the investigation in 1956, they confirmed that progressive accretion on the eastern sea reef would tend to widen the shallow tail more to the west, which becomes still shallower and extends its tail further south. The enlargement of the Sagar island, formation of other islands and sand shoals in this region are the primary evidences for sediment deposition in Sandhead region, which confirms with the results of the present study.

Rivers are identified as the major sources of sediments for the Indian coast. Ganges and Brahmaputra contribute a major share of suspended sediments to the Bay of Bengal, whereas Indus supplies more to the Arabian Sea. While the global river sediment discharge into the sea is 18×10^{12} kg/year, the Indian rivers contribute 1.2×10^{12} kg. Deposits in the gulfs, tidal marshes, bays, beach deposits and aeolian inland transports are found to be the primary sinks for the sediments moving along the Indian coast.

The present study indicates that the sinking of sediments is active at Gulf of Kachchh, Gulf of Khambhat, Gulf of Mannar, Palk Bay and Sandheads. The calculation shows an annual average deposition of sediments to a thickness of 0.025 m at Gulf of Kachchh, 0.03 m at Gulf of Khambhat, 0.010 m at Gulf of Mannar, 0.006 m at Palk Bay and 0.003 m at Sandheads. The depositional features identified in the present study have been noticed as occurrences of spits, shoals and the progradation of coastline. These sinks exist mostly in semi-permanent form, receiving more sediments during monsoon periods and supplying back sizable portion during the ensuing fair weather period to the littoral system. In addition to these sinks, the migration and enlargement of sand spits at various river mouths, deposition of littoral materials at Chilka Lake, Kakinada sand spit and at Rameswaram–Dhanuskodi exist as noticeable sinks along the Indian coast.

The construction of dams and implementation of soil erosion control programmes have greatly diminished the value of a river as a source of beach sand. The repercussions of the depletion in sediment supply to the littoral system are widely noticed, causing erosion. Encroachment of sea into the land has been commonly noticed near river mouths, particularly along the coasts of Karnataka and Kerala and Cauvery river mouth near Poompuhar due to the reduction in sediment supply and discharge, which also results in silting of the river mouth. The permanent loss of beach is due to wave energy concentration. The natural process may take few decades to modify the shoreline to bring a dynamically stable form. Next to rivers, the headlands and beach erosion contribute significantly as sources along the Indian coast. In addition to this, direct runoff and rainfall contribute to the loss of sediments from sub-aerial portion of the beach. Another minor loss is due to mining of beaches for sand and placer deposits.

On the other hand, lagoons, estuaries, beach storage, sand spits, siltation at harbour channels and formation of marshy lands act as main sinks for the sediments.

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Induction of *in vivo* somatic embryos from tea (*Camellia sinensis*) cotyledons

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Somatic embryos were obtained *in vivo* from tea seed cotyledons of three important Indian tea cultivars on moist sterile sand. *In vivo* embryogenesis was influenced by the incubation temperature, time of seed collection and genotypes. Out of the three cultivars, UPASI-9 was the most responsive (23.3 ± 0.59) during September, followed by T-78 (16.5 ± 0.84) during October and Kangra Jat (11.7 ± 0.69) during November. However, among the three different temperature regimes (24, 28 and 32°C), embryogenesis was noticed only at 28°C for all the cultivars. Histological evidence confirms somatic embryogenesis.

TEA (*Camellia sinensis*) is one of the most important plantation crops in the world. Although conventional breeding and vegetative propagation are the only means for plant improvement, they are slow, time consuming and labour intensive. Therefore, improvement through biotechnological means has tremendous potential to overcome the limitations of conventional approaches.

Embryogenesis is the most popular regeneration pathway of plants because of its wide applications[1]. Embryogenesis has been reported for most of the crop species[2,3]. The process has been successfully exploited for clonal propagation[4], artificial seed production[5], cryopreservation for the storage of elite clones[6], embryo rescue[7] and most importantly, *in vitro* manipulations through genetic transformation[8]. In *Camellia* too, somatic embryogenesis has been studied well and used for multiplication of elite clones[9], artificial seed production[10,11], embryo rescue of inter-specific crosses[12] and transgenic plant production[13]. In all the reports of embryogenesis, emphasis has been given to manipulate the nutrient composition, growth regulators in culture medium, physical conditions of incubation and other stress treatments to induce somatic embryos. However, induction of *in vivo* embryogenesis for any crop species has not been reported so far.

The present study was undertaken to germinate tea seeds under sterile conditions in steel boxes with moist sand, for the use of protoplast isolation. Although a chance observation, in this paper we report the induction of embryogenesis on cotyledon surface of mature tea seeds under *in vivo* conditions.

Mature fruits of the three cultivars, viz. UPASI-9, T-78 and Kangra Jat were collected from tagged bushes growing at Tea Experimental Station, Palampur, Himachal Pradesh, (1290 msl at 32°N and 78°S) during September–November. The reason for choosing these particular months was because seeds of these cultivars show highest embryogenic potential during these periods[14]. Among the cultivars, UPASI-9 is the most popular in South India, whereas T-78 and Kangra Jat are widely grown cultivars in north-east India and Kangra valley (Himachal Pradesh) respectively.

Seeds were separated from fruits and viability was tested by sinker-floater test[15]. Half of the sinker seeds of each cultivar was shown in field as per conventional procedure for control treatment[15]. The other half was washed thoroughly with Tween-80 for 5 min and then with distilled water for 6–8 times. Seeds were then surface-sterilized with 4% (w/v) calcium hypocholoride solution for 10 min followed by 5–6 washings in sterile de-ionized water. An additional treatment of 10 mg/l streptomycin sulphate was given for 25 min to avoid endogenous bacterial contamination.

A layer of 0.5 cm absorbent cotton was placed at the bottom of a steel box (22 cm diameter × 6 cm height) over-layered by a 4 cm thick sand mix (sand : activated charcoal :: 3 kg : 4 g). This was then moistened with 200 ml of distilled water and autoclaved at 104 kPa and at 121°C for 60 min. Fifteen seeds of each cultivar were inoculated in steel boxes under aseptic condition. Then, seeds of each cultivar were demarcated by placing autoclaved toothpick sticks between them. For identification, the respective position of the seed of each cultivar was marked outside the steel box.

The steel boxes were kept in dark in BOD incubators (Narang Scientific Works Pvt Ltd, New Delhi) at three different temperatures (24, 28 and 32°C) and observations were recorded after every 30 days. The experiments were

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