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Protocol for sampling and analysis of food and agricultural produces consequent to a nuclear accident in India

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ABSTRACT

Nuclear accidents, despite having an extremely low probability of occurrence, could cause uncontrolled release of radioactive elements (fission and activation products) into the environment, and may ultimately lead to contamination of food products. Such a scenario requires extraordinary measures for control of food, which might be contaminated to a level not suitable for human consumption. Agricultural products (which include grain crops, vegetable, fruits, dairy, meat, eggs and poultry) pass through a series of local, district and state level markets to finally reach consumers. An effective intervention at different stages of distribution by targeted sampling and analysis of suspected (contaminated) foodstuffs will substantially reduce the chances of contaminated food to reach the public. At the same time, it will also ensure food security of the people without imposing unreasonable restrictions in market flow. This can also help in getting the farmers adequately compensated. This paper presents a protocol for sampling and analysis suitable for India, considering the diversity with respect to climate, soil type, land use, crop pattern, population density, etc. The paper also provides an estimate of infrastructure requirement to carry out environmental monitoring following the emergency with respect to human resources and instruments. The paper proposes to use the national web portal for collection of data pertaining to crop pattern, land use and market flow. A web-based decision support system (Web-DSS) on a GIS platform, for sampling, analysis and display of data online would enhance the transparency of decision being taken and enable the administrators to effectively monitor the work flow, details of sample collection, analysis and effective use of human and other resources.

1. Introduction

Nuclear Power Plants (NPPs) have to comply with stringent regulations for airborne emission and discharge of radioactive elements to the environment. The International Atomic Energy Agency (IAEA) sets international safety standards that should be adhered with respect to site selection, baseline studies, safe operation and decommissioning of a nuclear power plant. In India, the Atomic Energy Regulatory Board (AERB) is the statutory body for ensuring that the use of nuclear energy does not cause undue risk to the health of workers, general public and the environment. AERB sets national norms and ensures that all NPPs in India comply with the regulatory requirements (AERB, 2014a; 2007; Kumar et al., 2017). The occupational exposures of employees are maintained well below the values specified by the regulator. The environmental release of radioactive effluents from NPPs are maintained significantly low following the doctrine of *ALARA (as low as reasonably achievable)*. The estimated doses to the public by the operation of NPPs in India is published every year in the annual reports of AERB, which are on an average less than 1% of the limits specified by AERB (AERB, 2018). Indian nuclear power plant authorities contributed in enhancing safety & reliability of nuclear power plants globally through its active participation in World Association of Nuclear Operators (WANO), CANDU Owners Group (COG), IAEA and other international organizations.

India mainly has pressurized heavy-water reactors (PHWR, CANDU Type) which are run by Nuclear Power Corporation of India Limited (NPCIL), a Public Sector Unit (PSU) under the administrative control of the Department of Atomic Energy (DAE) which in turn reports to Prime

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Minister's Office (PMO). The company (i.e. NPCIL) was registered as a Public Limited Company under the Companies Act, 1956 with the objectives of operating nuclear power plants and realising nuclear power projects for generation of electricity (NPCIL, 2020a).

Bhabha Atomic Research Centre (BARC) under Department of Atomic Energy, Government of India (DAE, GOI) has established Environmental Survey Laboratories (ESLs) at all the nuclear-power plant sites to monitor the radioactivity levels in the environment (air, soil and water). The ESLs are under direct administrative control of Environmental Monitoring & Assessment Division, BARC. ESLs carry out extensive environmental survey, collecting and analysing thousands of samples every year in the 30 km radial distance of Nuclear Power Plants (NPPs). Estimated external and internal doses thus obtained are reported to AERB every quarter. This is to demonstrate the regulatory compliance with respect to public dose during routine operations of the NPPs.

There are well laid procedures for the emergency preparedness in case of an accidental scenario with off-site consequences. AERB has laid down detailed protocols which are to be followed during off-site emergency scenarios and these procedures serve as guidelines for decision making pertaining to counter measures such as sheltering, evacuation and food control (AERB, 2014b; IAEA, 2015).

India has an agriculture dependent economic system and is one of the major suppliers of agricultural produce in the world market. Agriculture is one of the professions carried out by many members of population around our power plants. These agricultural products are partly used by the farmers themselves while a major part is exported to nearest towns and even to other countries. In the case of a nuclear accident/emergency, a large area around the power plant may get contaminated for a long period due to the release of radionuclides (Alexakhin et al., 1996; Saito et al., 2019). Controlling the consumption of food stuff, consequent to such an accident, is one of the counter measures that should be adopted (AERB, 2014b; IAEA, 2015).

However, in an agriculture driven market system, a full control by banning all the food stuff in a region could lead to food insecurity to the people dependent on it and account for unnecessary food wastage. Hence basic strategies for food control should followed to ensure the radiological safety of the public without imposing undue restrictions on the movement of agricultural produce. This strategy is in line with the on-going IAEA-CRP (Coordinated Research Project) on response to nuclear emergency affecting food and agriculture. Under this CRP, India has entered in a research agreement titled '*Development of a generic methodology for the estimation of contamination of food materials consequent to a nuclear accident (IAEA CRPD 1.50.15)*'. The CRP has been approved by DAE, India.

In case of severe natural calamities (Fukushima, 2011) or due to unforeseen circumstances (Chernobyl 1986) nuclear accidents may happen, leading to unrestrained release of radionuclides in the environment. In cases of such Beyond Design Basis Accidents (BDBA) such as Chernobyl and Fukushima; humans, animals, other biota and environment in the vicinity are potentially exposed to higher levels of radioactivity (Beresford et al., 2016; Haque et al., 2017; Mikami et al., 2015; Saito et al., 2015). Such unanticipated scenarios require adequate planning and rigorous decision support methods to mitigate the detrimental effects on human health and the environment (Alexakhin et al., 2007; Cipollaro and Lomonaco, 2016) and prompt decisions should be taken to keep the doses received by the public due to ingestion of food material within reasonable limits prescribed by ICRP (ICRP, 2012). Geographical Information System (GIS) is an effective scientific gateway which is greatly helping cases of unprecedented natural calamities by providing databases of the concerned areas and easily understandable visualization for prompt decision making (Goodchild, 2010; Konstantopoulos and Ikonomopoulos, 2015; Steiniger and Hunter, 2013).

India is a country with vast expanse (3.82 million square kilometres) with enormous geographic and climatic variations. The production and market flow of agricultural products vary widely from one site to other. This is necessary to consider in order to build a harmonized procedure for sampling and analysis of agricultural produces, in case of a nuclear accident which may affect agriculture and food products. India is mainly an agrarian country with almost 43% of its population is dependent upon food produced locally in their fields and milk produced by the livestock/cattle grazing locally (Lele and Goswami, 2020). India is in the tropical zone, and the nuclear power plants in the country are located at various geographic locations. The agricultural pattern in India, the food products cultivated, and the distribution pattern are quite different as compared to other developed countries. The country produces leafy vegetables, milk and meat with a shelf life of a few days to cereals and pulses which have shelf lives of more than a few months. Similarly, the distribution pattern of food products ranges from self-use by the farmers and export to other countries. Hence there is a necessity to develop suitable protocols for the sampling and analysis of food product unique for the country considering the local aspects. This will support the authorities in taking appropriate decisions with respect to food control in an accidental scenario, so that adverse impacts to the agricultural and food sector is minimum and consumers are adequately protected.

This paper presents the various characteristics of suitable food sampling and analysis protocol which takes care of complexity and diversity in Indian agricultural practices, crop patterns and food habits. The protocol is exclusively applicable in case of a nuclear or radiological emergency affecting food and agriculture in India. The protocol also presents an estimate of the infrastructure requirements required for sampling and analysis for radioactivity in food in an extended region of 100 km.

2. Materials and methods

2.1. Location of nuclear power plants in India

India is located in the southern region of Asia with its southern part bordered by the Indian Ocean, northern region by the Himalayas, western by the Arabian Sea and eastern by the Bay of Bengal. Geographically, the country is situated north of the equator, and has a geographic extent with 8°44′ to 37°6′ north latitude and 68°7′ to 97°25′ east longitude. It is the second largest country by population and seventh largest by area. The total population stands at 1.21 billion (Census 2011) while the total land area is 3,287,263 km^2 (Rajaram et al., 2008).

India entered into the nuclear science and technology era nearly sixty years ago with a well-known three-stage nuclear power program (Banerjee and Gupta, 2017). India's first commercial nuclear reactor was set up in Tarapur, Maharashtra in the year 1969 and since then, 21 more reactors have been installed. Electricity from nuclear reactors cater ~2% of the total electricity need in India (Central Electricity Authority, 2018). India has an ambitious nuclear power program under the Department of Atomic Energy. As per the country's statute, Nuclear Power Corporation of India Limited (NPCIL) is responsible for design, construction and operation of nuclear power reactors in India. The sites (Table 1), where power reactors are operational, are Tarapur, Maharashtra; Rawatbhatta, Rajasthan; Kalpakkam, Tamil Nadu; Narora, Uttar Pradesh; Kakrapara, Gujarat; Kaiga, Karnataka and Kudankulam, Tamil Nadu (NPCIL, 2020b). Location of India's NPP with a radial zone of ~30 km and ~100 km is shown in Fig. 1. More reactors are now under construction and are expected to be commissioned in the near future (NPCIL, 2020a). In addition to Pressurized Heavy Water Reactors (PHWR), which are the major contributors to the nuclear power production in India, two units of Boiling Water Reactor (BWR) and two units of Pressurized Light Water Reactors (PWR) are also operational.

2.2. Zonation around NPPs for emergency preparedness

AERB, in its emergency preparedness guide (EP-5), has recognized three zones for the purpose of preparedness in case of offsite affecting general public residing outside the 1–2 (1.6) km of exclusion zone which is isolated through site fencing (AERB, 2014b). The guidelines of AERB

Table 1
List of operational Nuclear Power Plants in India.

Plant Name	Unit	Type	Capacity (MWe)	Date of Commercial Operation
Tarapur Atomic Power Station (TAPS), Maharashtra	1	BWR	160	28.10.1969
Tarapur Atomic Power Station (TAPS), Maharashtra	2	BWR	160	28.10.1970
Tarapur Atomic Power Station (TAPS), Maharashtra	3	PHWR	540	18.08.2006
Tarapur Atomic Power Station (TAPS), Maharashtra	4	PHWR	540	12.09.2005
Rajasthan Atomic Power Station (RAPS), Rajasthan	1	PHWR	100	16.12.1973
Rajasthan Atomic Power Station (RAPS), Rajasthan	2	PHWR	200	01.04.1981
Rajasthan Atomic Power Station (RAPS), Rajasthan	3	PHWR	220	01.06.2000
Rajasthan Atomic Power Station (RAPS), Rajasthan	4	PHWR	220	23.12.2000
Rajasthan Atomic Power Station (RAPS), Rajasthan	5	PHWR	220	04.02.2010
Rajasthan Atomic Power Station (RAPS), Rajasthan	6	PHWR	220	31.03.2010
Madras Atomic Power Station (MAPS), Tamilnadu	1	PHWR	220	27.01.1984
Madras Atomic Power Station (MAPS), Tamilnadu	2	PHWR	220	21.03.1986
Kaiga Generating Station (KGS), Karnataka	1	PHWR	220	16.11.2000
Kaiga Generating Station (KGS), Karnataka	2	PHWR	220	16.03.2000
Kaiga Generating Station (KGS), Karnataka	3	PHWR	220	06.05.2007
Kaiga Generating Station (KGS), Karnataka	4	PHWR	220	20.01.2011
Kudankulam Nuclear Power Station (KKNPS), Tamilnadu	1	VVER -1000 (PWR)	1000	31.12.2014
Kudankulam Nuclear Power Station (KKNPS), Tamilnadu	2	VVER -1000 (PWR)	1000	31.03.2017
Narora Atomic Power Station (NAPS), Uttar Pradesh	1	PHWR	220	01.01.1991
Narora Atomic Power Station (NAPS), Uttar Pradesh	2	PHWR	220	01.07.1992
Kakrapar Atomic Power Station (KAPS), Gujarat	1	PHWR	220	06.05.1993
Kakrapar Atomic Power Station (KAPS), Gujarat	2	PHWR	220	01.09.1995

on the classifications of zones for effective implementation of protective actions are based on IAEA framework and recommendations from ICRP. The area around the site can be divided into following zones based on quantum and severity of release (Fig. 2):

a. A *Precautionary Action Zone* (PAZ), for facilities in hazard category I (nuclear reactors above 100 MW_{th}), where the goal of taking precautionary urgent protective actions, on the basis of conditions at the facility in order to reduce substantially the risk of severe deterministic health effects. This zone can extend up to 5 km.
b. An *Urgent Protective Action Planning Zone* (UPZ), for facilities in hazard category I or II, for which arrangements should be made for urgent protective action to be taken promptly as per state or centre's disaster management rules. Definitive planning for evacuation, sheltering and iodine-prophylaxis should be in place to avert doses. UPZ can extend up to 16 km.
c. *A Long-Term Protective Action Planning Zone* (LPZ) is a pre-designated region around a facility which extends up to 30 km from the NPP. The LPZ is the zone where provisions for effective execution of protective actions to lower the risk of deterministic and stochastic health effects from consumption of contaminated foodstuffs should be established in advance.

2.3. Agricultural production and consumption data

The agricultural pattern and market flow pattern of various parts of the country are available on government websites. Many Indian agricultural/animal products (wheat, rice, cotton, meat etc.) are exported to other countries (APEDA, 2018). Food consumption are available in the literature published from time to time by National Institute of Nutrition, India (NIN, 2011).

2.4. Infra structure requirement for monitoring

It is also necessary to equip the environmental monitoring labs with sufficient man power and instruments to cater to the needs of environmental monitoring, in case of an accident. This paper proposes a synchronized procedure for sampling, analysis and decision making with respect to control of food and agricultural produces, considering the site specific agricultural and market flow practices.

2.5. Environmental releases

Nuclear fission reactions lead to emission of gaseous radionuclides e.g. Fission Product Noble Gases (FPNGs), Ar-41, Tritium (in PHWRs) to the atmosphere and several other radionuclides which remain inside the nuclear reactor (as by-products of the fission reaction). Nuclear reactors are designed in such a way that majority of radionuclides remain in the reactor vessel itself while a few gaseous ones get released into the environment in a controlled manner. Liquid discharges from the reactors are also controlled to minimize public dose well within the limits. An individual member of public may get radiation doses from a NPP during normal operations via various pathways as shown in Fig. 3. The pathways of exposure through ingestion mode remain similar in emergency scenarios also.

3. Description of protocol for sampling and analysis

3.1. Optimizing the sampling collection

Subsequent to a nuclear accident, the process of sample collection and its analysis should be initiated as per the recommendations of IAEA and AERB (AERB, 2014b; IAEA, 2015, 1997). A generic guideline for sampling and analysis in an accidental scenario has already been prescribed in the AERB guidelines. The main aim of such sampling and analysis protocol is to establish a food control mechanism which will ascertain that no food item which is contaminated above a given threshold level (OIL7, discussed later) will be allowed to pass into the retail markets. The Fukushima Daiichi accident (Kutkov and Tkachenko, 2017) in Japan has been taken as a benchmark for establishment of protocols for soil sampling (Onda et al., 2015) and Food Monitoring Networks, FMNs (Brandhoff et al., 2016). It is also necessary that a screening test be done for food items which are self-procured or locally grown food in gardens, and consumed by individuals (Yamada et al., 2017).

The focal theme for establishment of a food monitoring network, in

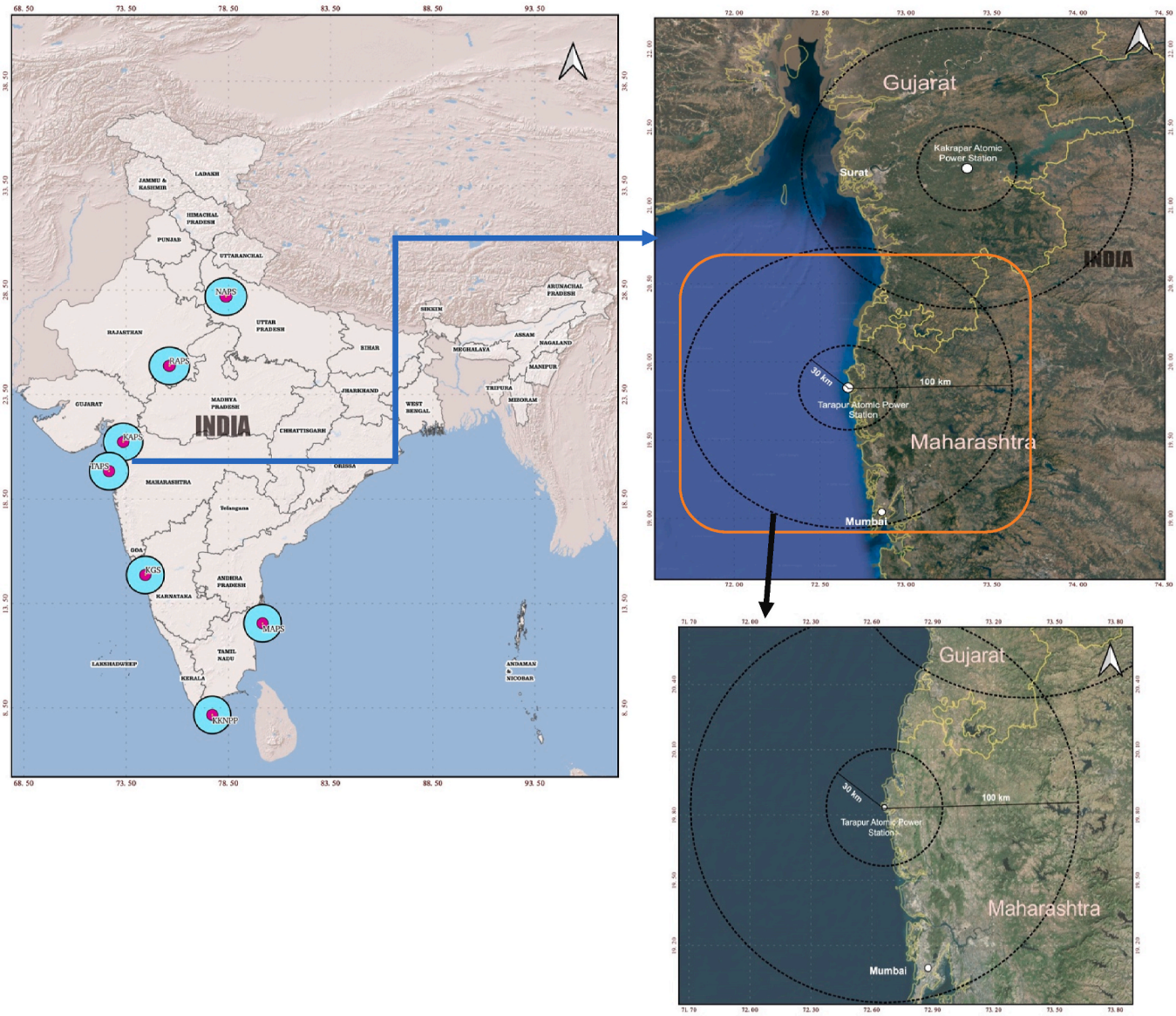

Fig. 1. Locations of Nuclear Power Plants (NPPs) in India with a radial zone of 30 km and 100 km.

which food items must pass through gamma-spectroscopy based instruments to find out typical gamma emitting radionuclides, is to effectively categorize food items which are:

(a) not fit for consumption,
(b) fit for consumption during nuclear emergency (contaminated below threshold level),
(c) fit for consumption after a few days/weeks/months and
(d) not at all contaminated.

These networks can be used in time of nuclear emergency to find out gamma-emitting radionuclides within a specified time scale. Table 2 provides a generic list of items that are likely to be contaminated and corresponding contaminants in case of a nuclear accident.

3.2. Operational intervention levels (OILs)

In case of a nuclear emergency, Atomic Energy Regulatory Board (AERB) of India has given elaborate, yet generic, set level of measurable quantity, which can be used as a guideline to take decisions for taking effective control over situation. These OILs are based on the guidelines provided by IAEA (IAEA, 2017) for protection of general public from harmful effects of ionizing radiation. OILs are typically expressed in terms of dose rates or of activity of radioactive material released, time integrated air concentrations, ground or surface concentrations, or activity concentrations of radionuclides in environmental, food or water samples. OILs are practical criteria that allow the prompt implementation of protective actions and other response actions on the basis of monitoring results that are readily available during a nuclear or radiological emergency.

The OILs proposed by AERB are based on IAEA recommendations in their safety guide series for emergency response (IAEA, 2002). A detailed guideline for preparation based on threat categories came in the year 2007 (IAEA, 2007). However, the incident of Fukushima in 2011, triggered nuclear regulatory agencies worldwide to develop faster decision-making criteria which will leave no ambiguity in the process of reliable & realizable decision making. In the year 2017, IAEA has come up with new set of OIL values in case of LWR (IAEA, 2017); the values and monitoring type has been tabulated in Table 3. For the sake of comparison of OILs recommended by IAEA in 2002, we have tabulated the OILs and the recommendation based on it in Table 4. The OILs help in making decision for the areas which are ought to be evacuated, the

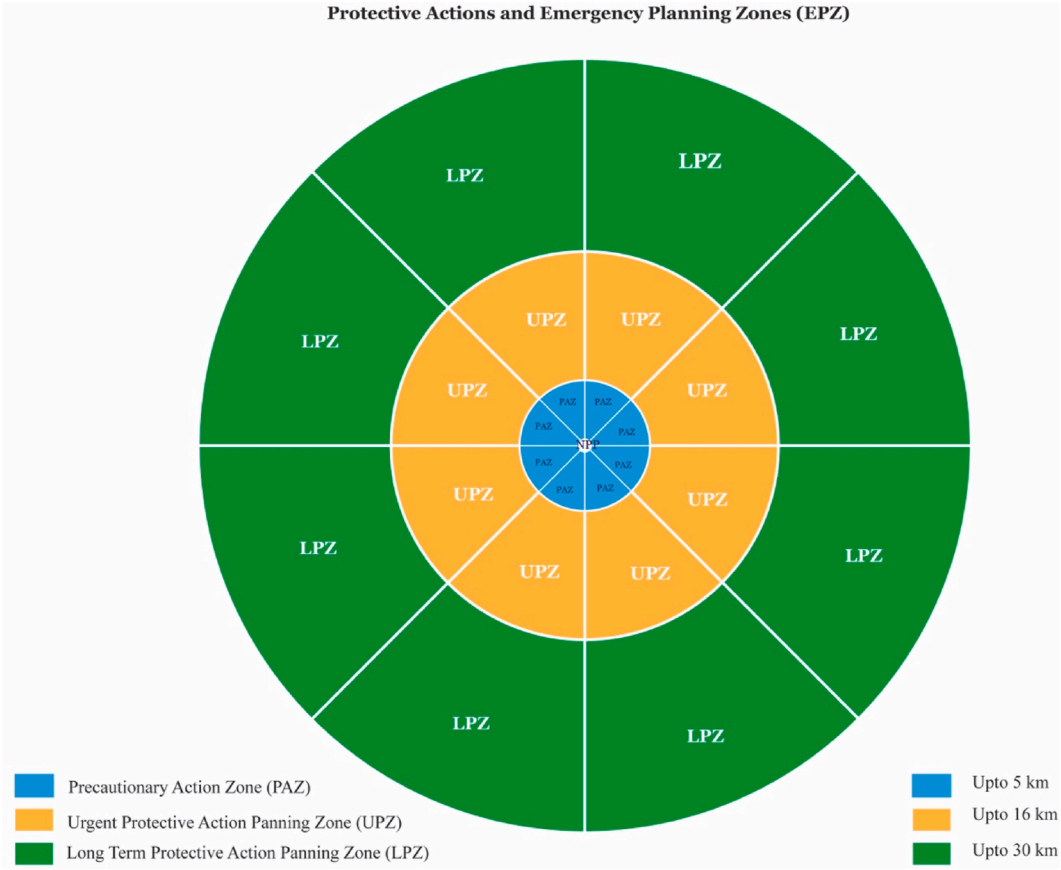

Fig. 2. Protective Actions and Emergency Planning Zones (EPZ) as per India's nuclear regulatory body (AERB).

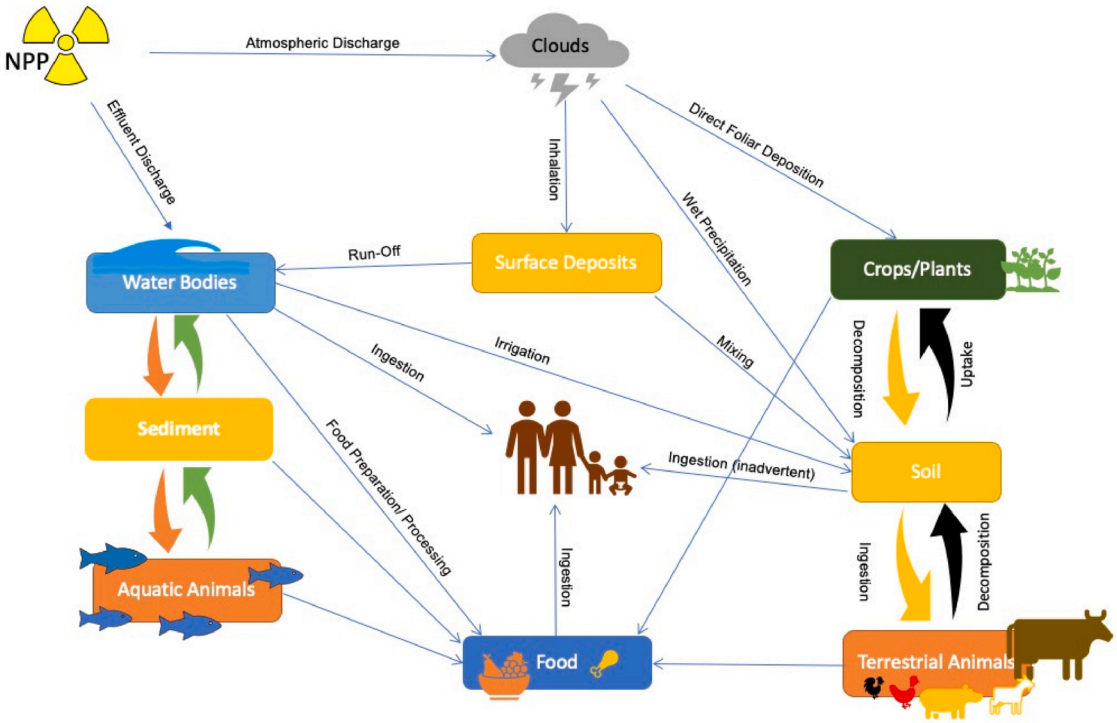

Fig. 3. Radionuclides originated from a nuclear power plant, during a nuclear accident, may end-up inside humans through various pathways (internal exposure through inhalation and ingestion).

Table 2
Most probable radionuclides contaminating food during nuclear incidents (IAEA, 1989).

Matrix	Radionuclides
Water	^{3}H, ^{89}Sr, ^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs
Milk	^{89}Sr, ^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs
Meat	^{134}Cs, ^{137}Cs
Vegetation	^{89}Sr, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{131}I, ^{134}Cs, ^{137}Cs, ^{144}Ce
Soil	^{90}Sr, ^{134}Cs, ^{137}Cs, ^{238}Pu, $^{239+240}Pu$, ^{241}Am, ^{242}Cm
Fresh water fish and Sea-food	^{54}Mn, ^{55}Fe, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{110m}Ag, ^{125}Sb, ^{131}I, ^{134}Cs, ^{137}Cs, ^{141}Ce, ^{144}Ce

Table 3
Default Operational Intervention Levels (OILs) values provided in IAEA publication 2017 (subscripts show type of radiation monitored, adapted from IAEA, 2017).

OIL	OIL Value	Monitoring Type
$OIL1_{\gamma}$	1000 μSv/h at 1 m	Ground monitoring: Ambient does equivalent rate at 1 m above ground level
$OIL2_{\gamma}$	1.100 μSv/h at 1 m	Ground Monitoring: For the first 10 days after reactor shutdown [a]
	2.25 μSv/h at 1 m	Ground Monitoring: Later than 10 days after reactor shutdown or for spent fuel
$OIL3_{\gamma}$	1 μSv/h at 1m [b]	Ground monitoring: Ambient does equivalent rate at 1 m above ground level
$OIL4_{\gamma}$	1 μSv/h at 10 cm from the skin [c]	Skin monitoring: Ambient dose equivalent rate at 10 cm from the bare skin of the hand and face
$OIL4_{\beta}$	1000 cps skin contamination	Skin monitoring: Beta count rate at 2 cm from the bare skin of the hand and face (The use of $OIL4_{\gamma}$ is preferable over $OIL4_{\beta}$)
OIL7	1000 Bq/kg of I-131 and 200 Bq/kg of Cs-137	Monitoring of food, milk and drinking water samples: Activity concentration of I-131 and Cs-137 in food, milk and drinking water samples
$OIL8_{\gamma}$	0.5 μSv/h	Thyroid monitoring: Ambient dose equivalent rate in front of the thyroid in contact with the skin

[d] The default value is provided in cps and not in Bq/cm^2 because instruments natively provide cps. When providing Bq/cm^2, an implicit assumption is made on the radionuclides being monitored. However, the radionuclide mix released from an NPP will be complex and changing, making the use of Bq/cm^2 impractical.
[e] Milk is mentioned separately because of its key role in radiation induced thyroid cancers following the accident at the Chernobyl NPP.
[f] I-131 and Cs-137 serve as marker radionuclides. A marker radionuclide is easier to identify and is representative of all the other radionuclides present, avoiding the need for costly and time intensive comprehensive isotopic analyses. The contribution of the other radionuclides expected to be present after a release of radioactive material.
[a] after the nuclear reaction in the core was stopped.
[b] The advantage of $OIL3_{\gamma}$ when compared with OIL7 is that, based on $OIL3_{\gamma}$, restrictions can be implemented early on in the emergency (i.e. when most needed) with readily available and easy to obtain ambient dose equivalent rates from deposition on the ground.
[c] The ambient dose equivalent rate $OIL4_{\gamma}$ is sufficient and preferable to assess the levels of radioactive material on the skin for a release of radioactive material from a nuclear power plant (NPP) or its spent fuel, because it is less dependent on the measurement technique and instrument characteristics. However, beta count rate $OIL4_{\beta}$ is also provided, since it may be used by some response organizations for skin monitoring.

distance up to which the food & agricultural sampling is required and the areas which are completely safe to be inhabited. AERB's emergency preparedness document guides the decision maker to collect samples from distances as far as 10 times to the distance where OIL3 has exceeded. It means if the farthest distance where OIL3 has increased from the NPP is found to be 3 km, then it becomes imperative to collect food samples from as long as 30 km from the NPP.

ICRP recommends an absorbed dose limit of 1 mSv for general public. The activity concentrations could be derived from this dose using

Table 4
Operational Intervention Levels (OILs) as recommended by Atomic Energy Regulatory Board of India (AERB).

OIL	OIL Value	Response Action (as appropriate) if the OIL is exceeded
OIL 1	γ-dose rate of 1000 μSv/h at 1m 2000 cps Direct Beta (β) 50 cps direct alpha (α)	Immediately Evacuate, Iodine Prophylaxis, Decontamination of Evacuees, STOP consumption of local produce and milk from animals grazing in area.
OIL 2	γ-dose rate of 100 μSv/h at 1m 200 cps Direct Beta (β) 10 cps direct alpha (α)	Iodine Prophylaxis, Stop Consumption of Local Produce & milk until it has been assessed by OIL 5 & OIL 6, Temporary relocation
OIL 3	γ-dose rate of 1 μSv/h at 1m 20 cps Direct Beta (β) 2 cps direct alpha (α)	Stop consumption of local produce & milk until it has been assessed by OIL 5 & OIL 6, Iodine Prophylaxis, Screen local produce up to an area 10 times the distance to which OIL 3 has exceeded
OIL 4	γ-dose rate of 1 μSv/h at 10 cm from the skin 1000 cps direct beta (β) skin contamination 50 cps direct alpha (α) skin contamination	Provide for skin decontamination and reduce inadvertent ingestion
OIL 5	Gross beta (β): 100 Bq/kg Or Gross alpha (α): 5 Bq/kg	Above OIL 5: Assess using OIL 6 Below OIL5: Safe for consumption during the emergency phase
OIL 6	Radionuclide concentration	Specific levels of Radionuclides in food.

equation (1):

$$GL = \frac{E}{M \times e_{ing} \times F} \tag{1}$$

Where, GL is the guideline level (Bq/kg);

E is the annual effective dose to the representative person (in this case, 1 mSv);
M is the mass of food consumed per year (kg);
e_{ing} is ingestion dose coefficient (mSv/Bq);
and F is the assumed contamination fraction (dimensionless).

Above equation (1) can be used for deciding guideline levels for different age groups. In the case of extensive contamination, a higher level of dose might be used. This would still be consistent with the IAEA guidelines, for existing exposure conditions. An annual effective dose to the representative person in the range of 1–20 mSv can be used to arrive at new guideline levels (GLs) (IAEA, 2016). It should be emphasized here that, depending on the severity of the food contamination, the doses can be set in the range of 20–100 mSv/year as per AERB guidelines.

Similarly the guidance levels for drinking water as provided by the CODEX and WHO (Table 8) apply to normal operational conditions of existing or new drinking-water supplies. These do not apply during an emergency exposure situation involving the release of radionuclides into the environment. However, the guidance levels apply again once the relevant authorities have declared an end to the emergency exposure situation.

The default values of the OIL set by IAEA are to be followed in the early phases of the off-site emergency so as to avoid any confusion due to lack of available data from the field. Thus OILs can be set on the basis of intervention levels (ILs) agreed upon during ongoing emergency period, based on prevailing conditions and enormity of the food contamination. It is should be set keeping in mind that it must not cause more harm than the overall benefit. The equation for OIL is (Eqn 2)

$$OIL = \frac{IL}{t \times f_1 \times f_2} \tag{2}$$

OIL Operational intervention level for food (Bq/kg).

IL Intervention dose for ingestion (20–100 mSv/y in case of nuclear emergency)
t integration time (1 year for long lived radionuclides, 40 days for I-131)
f_1 dose conversion factor for ingestion (Sv/Bq)
f_2 Relative contamination factor, quotient between the expected mean specific radionuclide activity in food during one year and the corresponding values for OILs (Kirchner and Wirth, 2007).

It should be noted that the dose from food & agro-products does not include doses from drinking water pathway and it should be properly compensated i.e. IL should comprise of dose from drinking water pathway + dose from food pathway, and should not exceed 100mSv/y. References are provided for OILs, their derivation and use in a phased manner. It would be beyond the scope of this paper to discuss it in detail.

3.3. *Preliminary data of agricultural produce and food products in India*

The Government of India (GOI), in collaboration with State Governments and Union Territories, publishes majority of its data on a

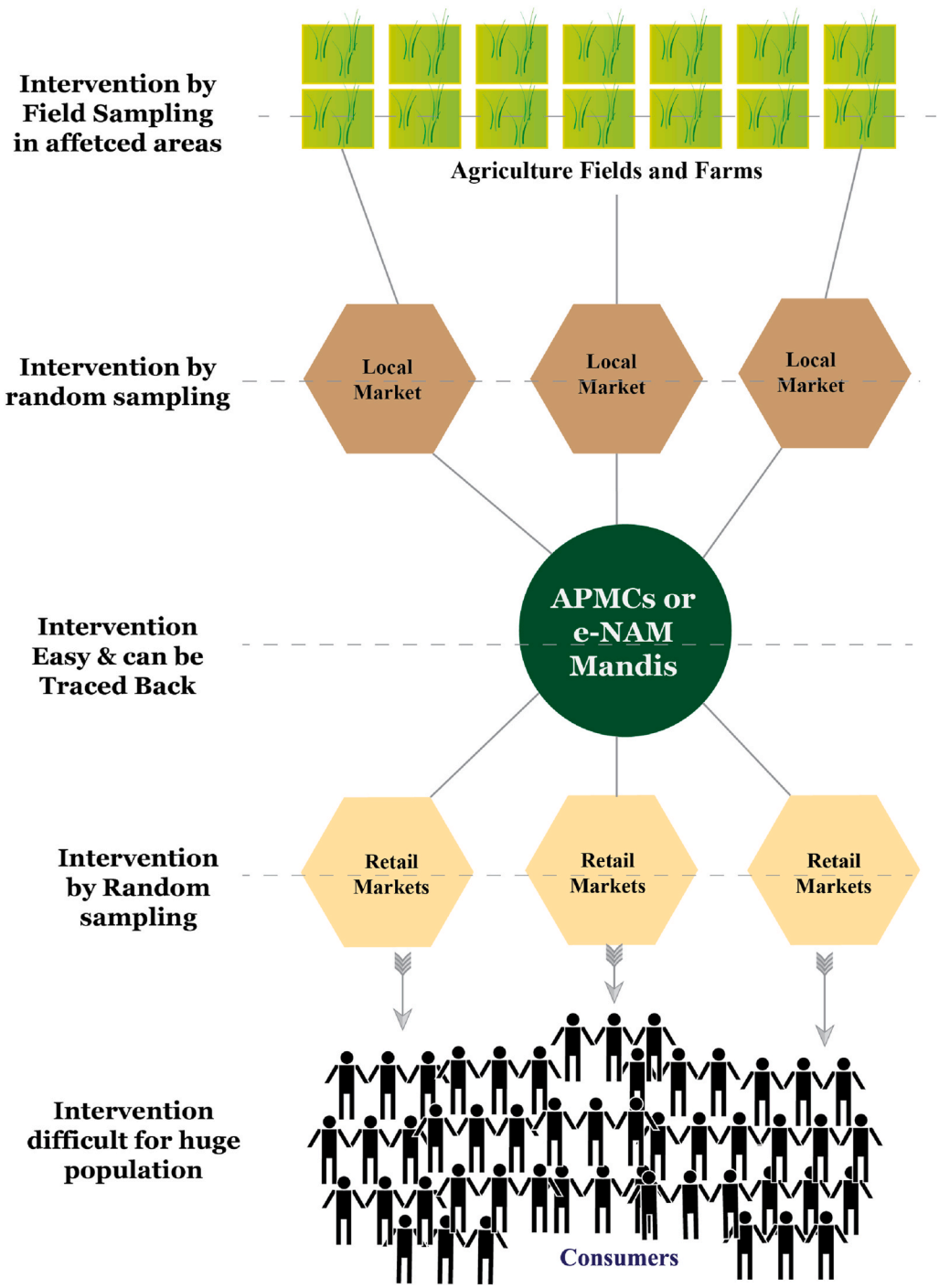

Fig. 4. A typical flow pattern of agricultural produces from field to consumer in India. Farmers transport their produce to local aggregation centres, which then gets transported by agro-businesses to the nearest wholesale market. Local retailers get their supply from the wholesale markets (APMCs or e-NAM mandis) and it ultimately reaches to consumers.

government-maintained site (GOI, 2020b). This Digital India initiative provides tens of thousands of data online in different formats e.g. CSV, XML, XLS, JSON etc. All the data on this site are provided free of cost under Open Data Policy which was brought out under National Data Sharing and Accessibility Policy (NDSAP), published in Gazette of Government of India (GOI) in 2012. The website is developed, published and maintained by National Information Centre (NIC).

3.4. Production and marketing of agricultural and food produces in India

India has a population of 1.21 billion and one-third of them are entirely dependent on agriculture as their only income and livelihood. Individual agricultural fields are very small in size ranging from less than a hectare to sometimes 10 ha. The decision-making process during emergency conditions depends largely on the site-specific information such as type of agricultural produce generated, their shelf life and its flow from producer to consumer. In addition to self-consumption of the agricultural produce, marketing outlets include organized agro-produce markets, wholesale big retail outlets and local markets. A typical flow of agricultural produce from the field to the consumer (individual) is shown in Fig. 4. The number of collection centres, wholesale markets and retail markets may vary depending upon the location, type of food articles and their demand. The extent of the chain from agriculture production or field to the consumer depends on the type of food, shelf life, production volume and its commercial value. The items which have high commercial potential are considered for export to other countries.

3.5. Geographical and crop variability

India is a country with immense geographical variations starting from permanently snow-laden greater Himalayan mountain-range to Thar deserts of Rajasthan, from huge Indo-Gangetic plains to hilly-areas of north-east which are covered with dense forest, from oldest Deccan plateaus to largest riverine delta of Sundarbans. Similarly, the cropping pattern, the crops and food habits also show a complex variation in their distribution pattern (Rajaram et al., 2008).

Hence it is necessary to harmonize the protocol so that it is generic for fast prompt decision making while there is facility to incorporate site specific features.

The whole process of decision making regarding the control on consumption of radioactivity-contaminated food involves the participation of the sampling team, radioactivity assessment team, data analysis team and the district administrators. For proper decision making, it is necessary to have.

a) Site-specific data regarding the agriculture and food production practices of the region around the nuclear facility.
b) Site-specific data regarding the product flow from the production centre to the consumer.
c) A quick sampling and analysis program to screen out the products having radioactivity above the reference levels from the rest, which are suitable for consumption.
d) A quick methodology of decision-making process.

This protocol is for the sampling and analysis of food and agricultural produce consequent to a nuclear accident at any of our operating facility, applicable for local/Indian conditions. The protocol covers the steps involved in site-specific data collection and representation in GIS platform. It starts with sampling of food and agricultural produce consequent to such a nuclear accident at any of our operating facility, pre-processing of samples, radiometric assay of samples, data analysis, representation of analytical data on a GIS platform and decision-making process with respect to control of food stuff (Fig. 5). As part of the CRPD 1.50.15, IAEA is making a GIS based decision making tool for the control of foodstuff consequent to such a nuclear accident. Due to inherent diversity in the food-habits, small size of crop fields of India, an altogether

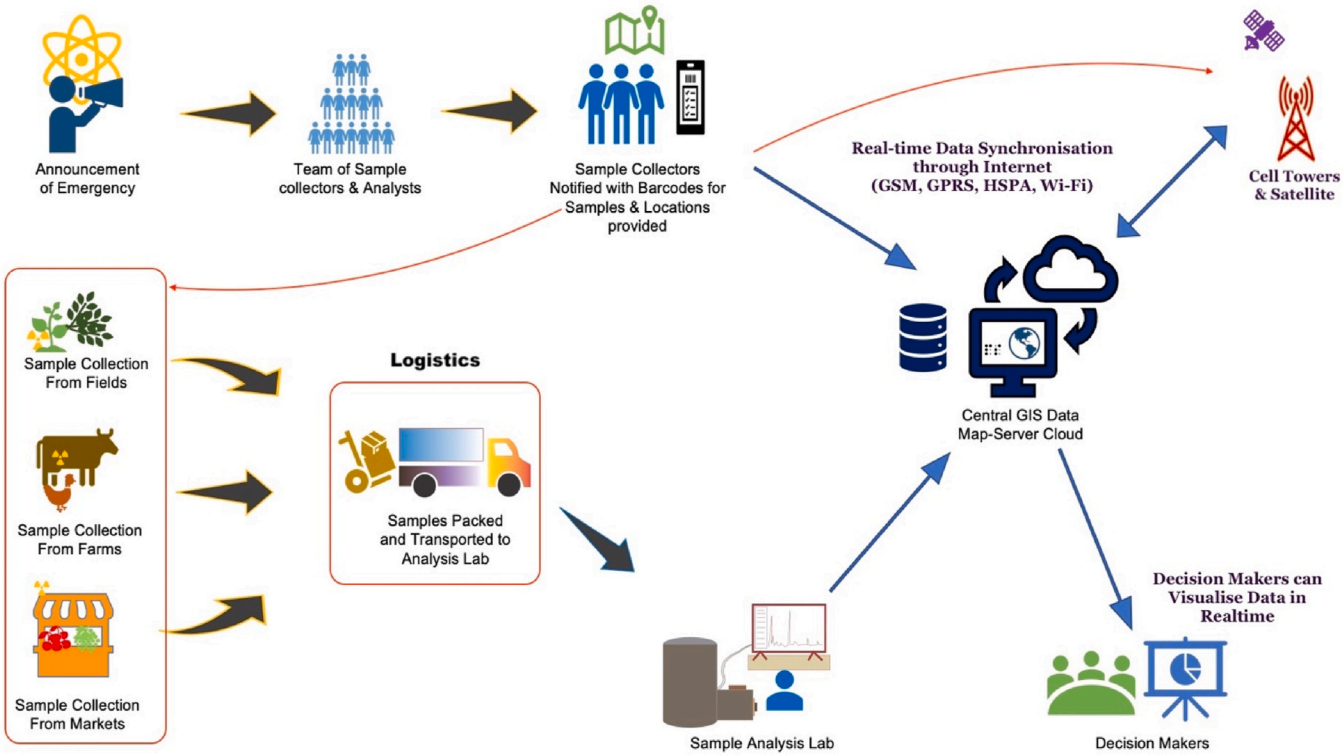

Fig. 5. An outline of the sample collection, distribution & decision-making process, where GIS and data visualization play the central role by connecting the decision maker(s) to the sample collectors, logistics team and to sample analysts. The data is synchronized in real-time and displayed in form of a dashboard, enabling decision makers to make swift and informed decisions.

different strategy may be required for effective sampling. The key features of the sampling and analysis of food and agricultural products are explained in this document.

3.6. Collection of site-specific data and presentation in GIS platform

It is to be emphasized that Long Term Protective Action Panning Zone (LPZ) in case of India is an area, defined by AERB in its Safety Guide (AERB, 2014), which is 30 km from respective power plants, however, a comprehensive data on production & marketing of agricultural/food products from each site, up to radial distance of 100 km is generated containing the following information:

3.6.1. GPS locations (Coordinate reference system)

The accuracy of a GIS location system lies in the accuracy and reliability of the data, which has been acquired from different sources. The data e.g. LULC, crop patterns, agricultural market flow etc., which has been collected in the beginning of the project was verified from different sources as well as by ground-truthing by physically surveying randomly selected areas around nuclear power plants.

3.6.2. Land use data

Nuclear Power Plants (NPPs) in India are located at 7 different locations of which three (TAPS, MAPS & KKNPP) are located near the seacoast and the other four (KAPS, RAPS, NAPS & KGS) are located near river/lakes. The land-use and land-cover (LULC) of each NPP differs from another. The pattern of LULC defines the sampling strategy. The land-use land-cover variations in India (Roy, 2015) is as follows:

d. Agricultural land
e. Grazing land
f. Forest land
g. Barren land
h. Waste Land
i. Others

3.6.3. Agricultural pattern data

a. Cereals
b. Pulses
c. Non-leafy vegetables
d. Leafy vegetables
e. Fruits & Nuts
f. Forest produces
g. Fodders (grazing)

3.6.4. Agricultural market flow data

In India, agricultural products are sold directly by the producers i.e. farmers themselves to either in the local markets or to a local aggregator, who buys directly from fields and then sells it in bulk to the local market. Many farmers with higher agricultural output transport it through trucks, minivans etc. and sell it through organized Agriculture Produce Markets (APMs) or National Agriculture Market (e-NAM) where they get better rates as compared to local market (eNAM, 2019). APMs include Government Regulated and privately controlled non-regulated markets. These markets now provide online rate-list as per commodity, daily intake and total traded amount. Farmers and businessman can register themselves on these portals and receive relevant details on their mobile phones. Large Agro-businesses or local retailers purchase agro-products from these markets and finally sell it to consumers after processing or without. Similar is the case with marketing of milk and meat. With respect to fodder, animals are partly fed through grazing and partly by the supply of grass.

4. Sampling and analysis objectives

The major spread of radioactivity arises due to the contamination of vegetation due to foliar deposition. The potential areas of contamination are identified based on the source term and meteorological data. It is expected that, after the radiological event, a daily report on contamination data will be provided by the authorities based on atmospheric dispersion models. This protocol does not cover the atmospheric dispersion methodology, since it is beyond the scope of this proposal. The priority of the sampling and analysis of agricultural produce is decided based on severity of radioactivity contamination, duration between the harvest and food consumption, type of use, amount of various materials used per individual per day and the market value. The sampling frequency and locations should be planned in way to ensure that food items assessed to have contamination beyond the regulatory limits are not consumed by the public. It is also necessary to segregate the uncontaminated foodstuff well within the shelf-life of the product, so that such foodstuffs are made available for supply to the market. Priority should be given to clearing the expensive items, perishables and food items of daily use to minimize the impact on economy as well as food security.

4.1. Type of samples to be considered for food control

It is necessary to identify the type of environmental samples that are likely to be consumed by the general public. This includes food product originating from plants, animals, and fodder products. Fodder can indirectly lead to the contamination of animal products. Following are the agricultural and food items needed to be considered for control and hence are to be sampled and analysed for radioactivity during emergency conditions.

4.1.1. Plant products

These products have been enlisted based on their production near NPPs and on their demand (food habits).

a. Leafy vegetable: Spinach, Cabbage, Mustard Leaf, Arbi, Methi (Fenugreek) Leaf etc.
b. Non-leafy vegetables: Potato, Tomato, Onion, Cauliflower, Carrot, Brinjal, Pumpkin, Bitter gourd, Bottle gourd etc.
c. Cereals: Wheat, Rice, Barley, Maize, Jowar (Sorghum), Bajra (Millets), Oats, Ragi (Finger millets) etc.
d. Pulses: Arhar (Pigeon pea), Chana (Bengal gram, Chickpea), Moong (Green gram), Masur (Lentil)etc.
e. Nuts: Cashew nut, Almonds, Dry-dates etc.
f. Fruits: Mango, Apple, Peach, Orange, Grape, Banana, Guava, Sapota, Papaya

4.1.2. Animal products

a. Milk: It is one of the chief components of Indian food. India is top milk producer in the world with a production capacity of 187.7 million tonnes of milk annually, and 28% of this milk is procured by village milk societies for processing. All India per capita availability of milk is 394 g per day, it varies between 71 g per day in Assam to 1120 g per day in Punjab (GOI, 2020a). Cows, buffaloes and goats, are major sources of milk in India. Boiled milk is essential food for infants, kids and adults in India. Milk is commonly added in tea and coffee, which are consumed all over the country.
b. Milk products: Curd, Yoghurt, Paneer (fresh cheese).
c. Meat: Mutton, Chicken-meat, Pork, Beef etc.
d. Egg: Hen, Duck & other birds

4.1.3. Fodder items

a. Grazing fields including leafy vegetation and grass edible for cattle.

Table 5
List of high value crops and fruits cultivated in India primarily around NPPs.

Crop/Vegetable/Fruit	Scientific name
Rice	*Oryza sativa*
Wheat	*Triticum aestivum*
Cotton seed	*Gossypium arboreum*
Maize	*Zea mays*
Sugarcane	*Saccharum officinarum*
Onion	*Allium cepa*
Tomato	*Solanum lycopersicum*
Black pepper	*Piper nigrum*
Potato	*Solanum tuberosum*
Mango	*Magnifera indica*
Gram	*Cicer arietinum*
Jowar	*Sorghum bicolor*
Banana	*Musa* sp.
Groundnut	*Arachis hypogaea*
Moong (Green Gram)	*Vigna radiata*
Arhar/Tur	*Cajanus cajan*
Horse-gram	*Macrotyloma uniflorum*
Urad	*Vigna mungo*
Cowpea (Lobia)	*Vigna unguiculata*
Coconut	*Cocos nucifers*
Soybean	*Glycine max*
Mustard	*Brassica juncea*
Pineapple	*Ananas comosus*
Dry ginger	*Zingiber officinale*
Cardamom	*Elettaria cardamomum*
Dry Chillies	*Capsicum annuum*
Turmeric	*Curcuma longa*
Sesamum (Til)	*Sesamum indicum*
Cashewnut	*Anacardium occidentale*

b. Stored leafy vegetation, grass and dried fodder provided to cattle.
c. Some of the major crops, vegetables and fruits which are grown in the district(s) where NPPs are located are given in Table 5. Their scientific names are also provided (GOI, 2014).

4.2. Prioritization of samples for clearance

Table 6 presents guidelines for prioritizing the sampling program during emergency conditions for plant products, animal products and fodder respectively. Leafy vegetables, non-leafy vegetables, fruits, milk, meat and green fodder, are to be given top priority during sampling.

4.3. Environmental sampling and data analysis

Information such as meteorological data and radioactive plume dispersal details are very important in deciding the focal areas during nuclear or radiological emergency, particularly in the initial phases. All the above information can be organised in spatial database with a Geographical Information System (GIS). The spatial visualization of agricultural production and distribution along with the probable areas of contamination will lead us to prioritize the areas where screening of food, fruit, water and agricultural products are to be carried out. The timely intervention will help in effectively controlling the contaminated agricultural produce from reaching to the public from affected areas.

Table 6
Guideline table for Prioritizing the Sampling and Analysis (Plant Products, unprocessed animal products and fodder for animals).

Food Item	Max. duration between harvest & consumption	100% to be cleared within
Leafy vegetables and fruits	1 week	3 days
Non-leafy vegetable/ tubers	1 month	15 days
Cereals	6 months	2 months
Pulses	6 months	2 months
Nuts	1 month	15 days
Spices	6 months	2 months
Herbs	6 months	2 months
Unprocessed Animal Products		
Milk	1 day	1 day
Fish/Meat	1 day	1 day
Fodder Items		
Green fodder from grazing land	2 days	1 day
Dry fodder	1 month	1 month

5. Human resources and infrastructure requirement for sampling and analysis

The 21st century has revolutionized the transport system throughout the world and India is also not far behind. Fresh food items travel via trucks, train, air-cargo and through waterways much faster than they used to travel 50 years ago. Metro cities in India like Delhi, Mumbai, Chennai & Kolkata, get their milk and vegetables supply from areas as far as 300 km after an overnight journey. Thus, it may be required that we must collect samples from areas up to 100 km radial distance on a daily/weekly basis until the area is cleared. In cases of nuclear emergency, the nearby areas from the location of NPP are likely to be more contaminated that those which are farther. Hence the sampling areas are demarcated as radial matrix (Fig. 6). In this matrix, the number of sample collectors (per km^2) have been allocated in the sectors which are near to the NPP i.e. to cover all the crop fields more effectively, while the same has been reduced for higher distances. The methodology for the deployment of human resources for sampling is provided in Table 7, assuming that the land and agriculture area is uniformly distributed. However, actual human resources requirement must be calculated for each site considering the site-specific parameters.

The total area of the quadrant was calculated by simple formula:

⇒ Total area of Quadrant (Q) = [(Area of Outer Radial Circle (C_o) – Area of Inner Radial Circle (C_i))]/4
⇒ $Q = (C_o - C_i)/4$

In case of nuclear emergency, the nearby quadrants are supposed to be more contaminated and a more exhaustive sampling would be required on daily basis. At the same time, as the total area increases with increasing radial distance, more volunteers are needed to collect representative samples from distant locations efficiently. Therefore, it is necessary to distribute human resources in such a way that each volunteer must collect more samples in nearby areas of nuclear power plant while a smaller number of samples will be collected from farther sites in a radial distance of 100 km. The human resources for sampling can be fulfilled from different units of DAE and if required University students can be asked to volunteer.

5.1. Sampling and sample barcoding

Sample collection for analysis of food & crop is supposed to start immediately after the declaration of the off-site emergency around a NPP by the national authority. Based on OIL3, samples will be collected from the regions which are supposed to be contaminated from radionuclides dispersed and deposited on crops, food and soil. For effective sampling and proper analysis of the samples, the region is divided into 16 radial sectors and 6 circular sectors of an incremental radius of 5 km each (i.e. 5, 10, 15, 20, 25 & 30 km). These resultant sectors will again be divided into small hexagonal regions of equal sides of ~400 m (Area = 0.42 sq. km).

All the sampling grids thus generated will be given a unique code which will be used to generate barcodes for sample collection. Adequate quantities of samples are to be collected by keeping in mind the type of radioactivity assay planned for screening the materials. Samples are to be barcoded to ensure the identity. A barcode will contain the following information depending upon the stage of the sample collection:

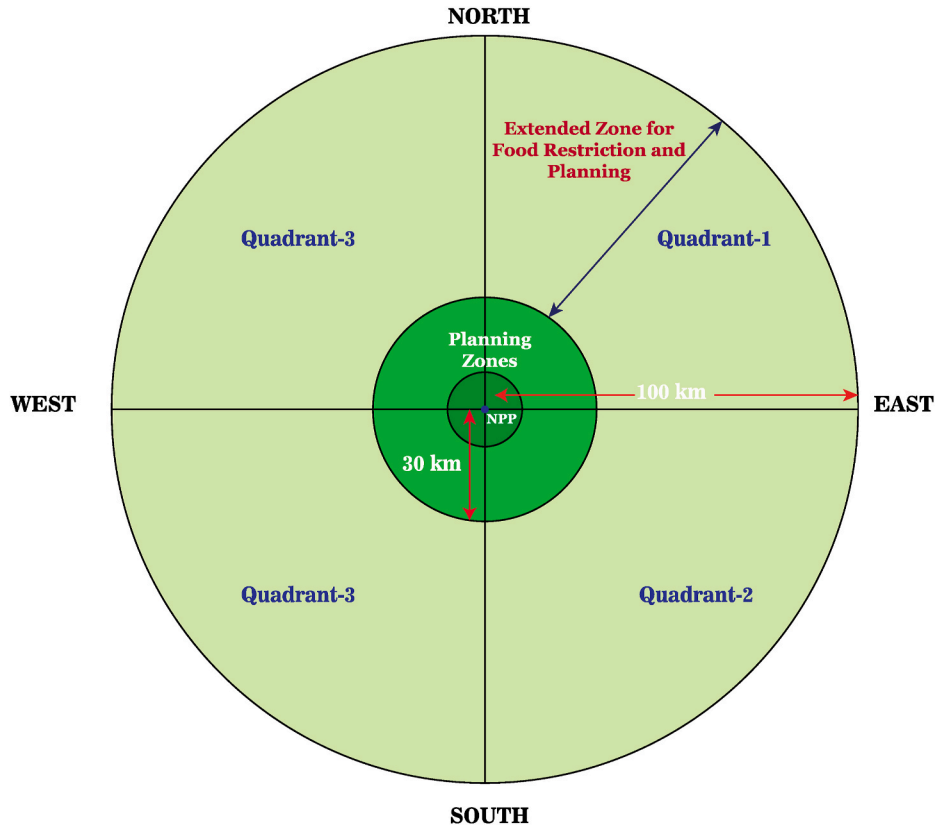

Fig. 6. Proposed quadrants with buffer distance of up to 100 km from a Nuclear Power Plant (NPP) in the centre. Radial distance for food and crop monitoring may vary depending on severity of accident conditions i.e. it may not even cover LPZ (30 km) or may extend beyond 100 km.

1. Grid Code
2. Sample team code (Team ID, individual ID)
3. Location Name or Latitude, Longitude of Sample Collection
4. Sample Type: Leafy vegetables, Non-leafy vegetables, Cereals, Pulses, Fodder, Milk, Meat etc.
5. Weight of sample
6. Date of collection
7. Dose rate measured by survey meter, ~1 m above ground.
8. Identification code of Analysing Lab
9. Identification code of Analyst

5.2. Sample processing

The sample processing will be carried out at Laboratory as per standard procedures for various radioactivity measurements (Hegde, A. G., 1998; IAEA, 1989). The compressible samples, such as leaves, fodders, etc. should be packed in pre-weighed polypropylene container, pressed with known weight into a standard geometry. Non-compressible samples should be packed in pre-weighed standard containers.

5.3. Estimation of activity concentration of radionuclides in samples

Although several radionuclides can be discharged following a nuclear emergency, some are very short-lived, and others do not readily transfer to the food. Radionuclides produced from nuclear installations and which can get incorporated in food chain are: ^{3}H, ^{14}C, ^{99}Tc, ^{35}S, ^{60}Co, ^{89}Sr, ^{90}Sr, ^{103}Ru, ^{106}Ru, ^{129}I, ^{131}I^{235}U, ^{238}Pu, $^{239\text{-}240}$Pu, ^{134}Cs, ^{137}Cs, ^{103}Ce, ^{192}Ir and ^{241}Am. The radionuclides of concern with possible transfer to foods products have been considered when setting the Codex Guideline levels. Amongst these, Iodine-131(^{131}I) which has good yield and is mainly in gaseous form, could be distributed over a wide area including crops/forage and is rapidly transferred from contaminated feed to the milk. However, ^{131}I has a relatively short half-live and decays within a few weeks. In contrast, radioactive Caesium (^{134}Cs and ^{137}Cs) is longer-lived (^{134}Cs has a half-life of about 2 years and ^{137}Cs has a half-life of about 30 years) and can remain in the environment for a long-time. Radioactive caesium is also relatively rapidly transferred from feed to milk. Uptake of caesium into food is also of long-term concern (WHO, 2011). Hence, analysis of ^{131}I,^{134}Cs and^{137}Cs is very important in food and agricultural produces during and afterwards of a nuclear emergency.

Gamma spectrometric technique is one of the best non-destructive methods for the rapid analysis of gamma emitters. Since ^{131}I (364.5 keV–81.2%),^{134}Cs (604.7 keV–97.6%) and ^{137}Cs (661.6 keV–85%) are beta – gamma emitters, they can be analysed easily using gamma spectrometric technique. Since these nuclides are multi-gamma emitters, for the detailed quantification of activity, HPGe based spectrometers are preferred. However, initial screening can be carried out quickly using NaI (Tl) scintillator-based spectrometers. Since NaI (Tl) based systems are more sensitive and easier to operate, it can be deployed even in mobile platforms for onsite assessment. The counting period required for the samples must be decided based on the sensitivity of the monitoring system and regulatory or clearance limits for the food and agricultural products. Efforts are to be made to use simultaneously more counting systems to accommodate maximum number of sample analysis collected by the survey team and minimizing the backlog. It is also ensured that the entire assay systems deployed for screening and assessment, are well calibrated for the radionuclides and type of samples.

5.3.1. Rapid and high throughput gamma counting

An HPGe gamma spectrometry system available with ESLs can count a sample in 10 min, which includes swapping of samples, for an MDA of 2.5 Bq/kg (Cs & Iodine isotopes). Assuming one HPGe is available for 24

Table 7
Human Resource requirement for sampling of food & agro-products.

Distance (km)	Quadrants	Area of Quadrant (km^2)[a]	No. of Samples per Collector	No. of Sample Collectors	Area Covered Per Sample Collector (km^2)[a]
Fencepost to 10 km	Quadrant −1	77	9	35	2
	Quadrant −2	77	9	35	2
	Quadrant −3	77	9	35	2
	Quadrant −4	77	9	35	2
10 to 20 km	Quadrant −1	236	7	35	7
	Quadrant −2	236	7	35	7
	Quadrant −3	236	7	35	7
	Quadrant −4	236	7	35	7
20 to 30 km	Quadrant −1	393	5	40	10
	Quadrant −2	393	5	40	10
	Quadrant −3	393	5	40	10
	Quadrant −4	393	5	40	10
30 to 40 km	Quadrant −1	550	3	53	10
	Quadrant −2	550	3	53	10
	Quadrant −3	550	3	53	10
	Quadrant −4	550	3	53	10
40 to 50 km	Quadrant −1	707	3	68	10
	Quadrant −2	707	3	68	10
	Quadrant −3	707	3	68	10
	Quadrant −4	707	3	68	10
50 to 60 km	Quadrant −1	864	2	85	10
	Quadrant −2	864	2	85	10
	Quadrant −3	864	2	85	10
	Quadrant −4	864	2	85	10
60 to 70 km	Quadrant −1	1021	2	100	10
	Quadrant −2	1021	2	100	10
	Quadrant −3	1021	2	100	10
	Quadrant −4	1021	2	100	10
70 to 80 km	Quadrant −1	1178	2	120	10
	Quadrant −2	1178	2	120	10
	Quadrant −3	1178	2	120	10
	Quadrant −4	1178	2	120	10
80 to 90 km	Quadrant −1	1335	2	140	10
	Quadrant −2	1335	2	140	10
	Quadrant −3	1335	2	140	10
	Quadrant −4	1335	2	140	10
90 to 100 km	Quadrant −1	1492	2	150	10
	Quadrant −2	1492	2	150	10
	Quadrant −3	1492	2	150	10
	Quadrant −4	1492	2	150	10
Total	40	31,394		~3300	

[a] The values rounded to whole numbers.

Table 8
CODEX Guideline Levels (GLs) for maximum allowable limits of Radionuclides in Foods after a Nuclear or Radiological Emergency for Use in International Trade, and WHO Guidelines for Radionuclides in Drinking Water. These GLs are used as values which must be attained before announcing the end of an off-site emergency (i.e., baseline levels which should be achieved before the end of emergency period).

Product Name	Representative Radionuclide	Guideline Level (Bq/kg) in food and Bq/L in drinking water
Infants Food	^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Am	1
	^{90}Sr, ^{106}Ru, ^{129}I, ^{131}I, ^{235}U	100
	^{35}S, ^{60}Co, ^{89}Sr, ^{103}Ru, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{192}Ir	1000
	^{3}H, ^{14}C, ^{99}Tc	1000
Foods other than Infant Food	^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Am	10
	^{90}Sr, ^{106}Ru, ^{129}I, ^{131}I, ^{235}U	100
	^{35}S, ^{60}Co, ^{89}Sr, ^{103}Ru, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{192}Ir	1000
	^{3}H, ^{14}C, ^{99}Tc	10,000
Drinking Water (WHO)		
	^{3}H	10,000
	^{14}C	100
	^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs, ^{238}U	10
	^{226}Ra, ^{228}Th, ^{230}Th, ^{232}Th, ^{234}U, ^{239}Pu, ^{241}Am	1
	^{210}Pb, ^{210}Po, ^{228}Ra	0.1

h a day, 144 such samples can be counted per day. In order to take a load of 2200 samples per day, it is necessary to have about 20 such HPGe systems. It will be ideal to deploy such assay systems (HPGe or NaI(Tl)) available in Environmental Survey Laboratories (ESL) and Emergency Response Centres (ERC) functioning around the nuclear facilities for activity analysis of samples with shorter shelf lives. The samples of larger shelf lives are proposed to be sent for analysis to facilities present at the nearest departmental labs/universities. The calibration and standardization of the systems have been carried out as per the international protocols (IAEA 1989).

It has to be understood that the sampling and analysis of food, agricultural products and water will have to continue (and restrictions for their consumption thereof) until activities of major radionuclides reduces to the guidance levels provided by CODEX and WHO (Codex--Alimentarius, 2006; WHO, 2011) drinking water and foodstuffs (Table 8). This also applies for international trades i.e. other countries will start accepting food and agricultural products only when these guidance levels are reached.

5.3.2. *Energy calibration*

The objective of energy calibration is to derive a relationship between peak position in the spectrum and the corresponding gamma-ray energy. The energy calibration includes the calculation of two sets of

parameters: the energy versus the channel number, and the peak shape or FWHM (Full Width at Half Maximum) versus the energy.

The spectrometry system has been calibrated covering the energy range of 46–2614 keV which includes all the gamma energies of the fission and activation products.

5.3.3. Efficiency calibration

In gamma spectrometry, our intention is to relate the peak area in our spectrum to the amount of radioactivity it represents. For this, we need the absolute full energy peak efficiency. This relates the peak area, at a particular energy, to the number of gamma-rays emitted by the source and must depend upon the geometrical arrangement of source and detector.

Efficiency calibration of the system has been carried out using IAEA certified reference materials in various matrices and geometries. Geometries normally used for the calibration are 50 cc, 100 cc and 250 cc cylindrical plastic containers. It was found out that for the food product analysis, 250 cc geometry is best suited for the better minimum detectable activity (MDA). Efficiency calibration is needed for each source-detector combination. The generally accepted analytical expression used for fitting the absolute efficiency data is as follows:

$$\log \in = a1 + a_2 (\log E) + a3 (\log E)^2 + a4 (\log E)^3 + a5 (\log E)^4$$

$\in$ = Full energy peak efficiency%
E = Energy (keV)

A single 4th or 5th order logarithmic polynomial can also be used for the entire energy range of 46–2614 keV.

A QA/QC of the system deployed must be performed according to existing international norms.

5.3.4. Minimum detectable activity (MDA)

The MDA is the minimum amount of radioactive nuclide that be confidently detected. It is equated to the activity equivalent of the limit of detection, LD. A generally accepted expression for the estimate of the detection limits, which is frequently referred to as the lower limit of detection (LLD) and which contains a pre-selected risk of 5% of concluding falsely that activity is present and a 95% degree of confidence for detecting the presence of activity. Table 9 shows the MDA for 1000 seconds spectrum acquisition and 250 g sample size. It can be seen that MDA values are much lower than the intervention levels specified by the regulator. The actual derived intervention levels for different foodstuff depend upon the amount of food taken. Hence, derived values should be based on national intake data published by National Institute of Nutrition, INDIA (NIN, 2011).

6. Conceptual steps involved in decision making during emergency situation

A brief conceptual outline of the steps followed for decision making (Fig. 5), in case of a radiological or nuclear emergency, can be given as follows:

Table 9
Minimum Detectable Activity (MDA) levels of Radionuclides in food products (as per infrastructure available in India) and the Intervention levels given by IAEA/FAO.

Nuclide	MDA Bq/kg (1000s) presently with ESLs (India)	IAEA/FAO Intervention levels for food items (Bq/kg)
I-131	3	100
Cs-134	2.5	1000
Cs-137	2.5	1000

Detector: Co-axial HPGe p-type, Relative Efficiency: 50%, Geometry: 250 g Cylindrical Box.
Standard: IAEA Reference (food material).

a) Announcement of Radiological or Nuclear Emergency
b) A centralized monitoring station with a set of decision makers (DMs) is set up
c) A GIS decision support system (Web-DSS) with real-time updates is set up with all the databases which were collected beforehand. It will also populate a spatial database, which will handle data collected during the emergency period.
d) Suitable locations for sample-collection kits, sample storage and sample analysis are marked
e) Sample collectors (SCs) and sample analysts (SAs), suitably trained for such scenarios, are briefed about the basics of the Decision Support System (DSS)
f) Sample collectors will be provided with sampling kit, radiation survey meter and an Android/iOS device with an 'application' (App) capable of communicating location data and various other relevant data to the central monitoring station in real-time. The communication could be through GSM, 3G, 4G or through wi-fi portals.
g) The Web-DSS at the Central monitoring station will automatically allocate regions, locations and frequencies of sample collection to the SCs on their android devices. This is based on network analysis, a common GIS solution. It can be overridden by the Decision Makers as per requirement.
h) Sample collectors will collect the samples, pack it properly and will update relevant details through their mobile application. The sample will then be collected by logistics team and will be forwarded to the Sample Analysts.
i) Sample analysts (SAs) at different samples analysis centres will start analysing the samples. The analyst's computer will be connected to the DSS via internet.
j) After analysis the output results (activity concentration of radionuclides) will be entered into the central database.
k) Depending upon the results of ambient radiation dose rate (μSv/h), submitted by the SCs, and results of activity concentration by SAs in (Bq/kg), the web-DSS would project the sampling grids into different colours. These colour coding might be decided by the Decision Makers and may be updated from time to time.

The overall result of such scenario is hypothetically depicted in Fig. 7 where the regions (hexagonal sampling grids) are color-coded depending upon the activity concentration a gamma emitting radionuclide in crop samples. Similar grids will be created for milk, meat and other food products and will be automatically updated according to the contamination levels.

7. Survey of agro-product markets and e-NAM

In India, there are several Agro-Product Market Centres (APMCs), now being connected through a central government regulated portal National Agriculture Market (eNAM), which work as large collection centres for different types of agriculture produce like crops, vegetables, fruits, milk, eggs, poultry etc. from nearby districts. There are more than 2477 principal regulated markets and 4843 sub-market yards regulated by the respective APMCs in India. A large proportion of the agricultural produce gets distributed in pan- India and the world through APMCs and eNAM. APMCs are crucial place for carrying out radiation survey and screening of food products. The incoming vehicles can be easily screened for gamma emitting radionuclides. The Location data of APMCs (in total 625) with all other relevant data, e.g. type of agro-product(s), types of storage facilities, phone-numbers etc., around the NPPs were collected from different state government managed websites and will be 'geo-tagged' (a georeferenced location, which has Latitude & Longitude data linked with other non-spatial data) on Google Earth and Google Map. The geo-tagged data, also called a point-data, can imported in QGIS (previously known as Quantum GIS) ver. 2.18.4, Las Palmas de G.C, which is an open source software for GIS based project (QGIS Team, 2018). Several attributes are added to the list of Agro Produce Markets e.

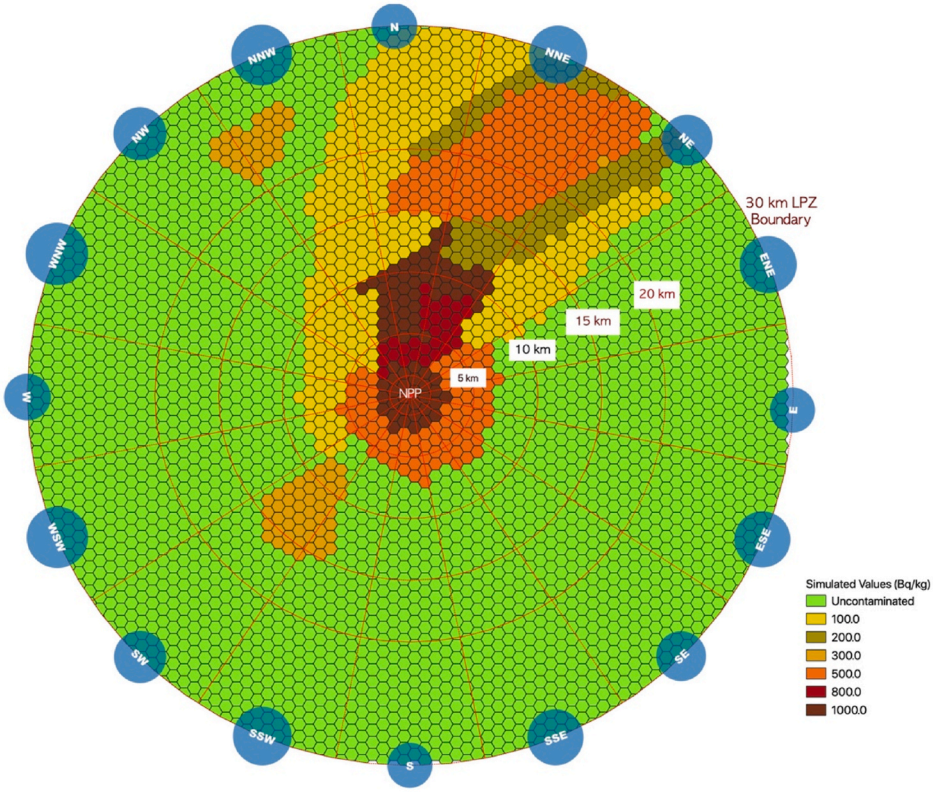

Fig. 7. A hypothetical scenario of sample analysis results visualization based on with color-coding of the sample (hex) grid, where hex-grids are colored according to the radioactivity of sample collected. Green cells represent crops considered safe to consume and are below a threshold of 100 Bq/kg. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

g. address details, kind of products, types of warehouse, etc. QGIS can handle almost any kind of data e.g. image, csv, shapefile, GeoJSON, OpenStreetMap, delimited text, MapInfo and Arc-info files etc. It can also be connected to other web-map servers online and can interact with several database type e.g. PostGIS, MSSQL, SpatialLite and PostgreSQL (QGIS, 2018). The GIS platform makes all the data available in one place. QGIS is an open source and freely available software and is being extensively used for grid generation; attribute handling, query & geo-spatial calculations. QGIS works seamlessly with majority of file extensions used in the field of GIS.

A thematic map for state-wise APMCs, which will be covered for monitoring purposes and location of nuclear power plants, is depicted in Fig. 8.

8. Conclusion

Chernobyl in 1986 and Fukushima in 2011 have invoked responses from various regulatory bodies around the world, especially from FAO & IAEA for more thorough and comprehensive methods of emergency preparedness regarding agriculture and food produce. The new approach must include real-time updates using GIS (an amalgamation of geospatial technology with information technologies), artificial intelligence, big data analytics and machine learning processes to expedite and assist in the overall process of decision making. Apart from ensuring safety of public from direct exposure from radionuclides, it is also equally important to safeguard the agricultural produce (crops, fruits, processed food, milk, meat, poultry and cattle) in the market as well as in field. It is pertinent that effective protocols and adequate human resources should be in place to minimize unwarranted wastage of agro-products with lesser shelf-life. This becomes much more relevant in developing countries, like India, where food security is a major issue in rural areas (Bhuyan et al., 2020). Furthermore, India has a huge population of 1210 millions (as per census of 2011) which is only second to China. Under the aegis of IAEA/FAO collaborative research project (CRP D1.50.15) an interdisciplinary team from Bhabha Atomic Research Centre (BARC, Department of Atomic Energy, India) has put up their best efforts to come up with a protocol which will be suitable for a country as diverse as ours. The protocol presented in this document is based on the broad guidelines of AERB, ICRP, IAEA, WHO and Codex-Alimentarius. The same protocol after initial submission to IAEA/FAO, will be submitted to Department of Atomic Energy (DAE), and AERB, for discussion and final approval.

Nuclear reactor(s) in a power plant is made extremely safe by introduction of defence in depth concept and by assigning safety a top priority (INSAG, 1996). The safety aspects to which nuclear industry adheres to is unparalleled, and to uphold this culture, nuclear power plants must develop new protocols and upgrade its infrastructure with time. BARC has established Environmental Survey Laboratories (ESLs) at all the NPPs in India and is accountable for the extensive environmental survey in a radial distance of 30 km. ESLs carry out sampling, radiation survey and analyse more than ten thousand samples to make sure that no member of public receives a dose more than 1 mSv and no undue built-up of radionuclides ensues in environmental matrices due to operation of NPPs and other nuclear activities. BARC, therefore, has been appropriately entrusted for the task to develop a sampling protocol for food and agriculture.

This document recommends a protocol for environmental sampling, processing, analysis and decision-making process for control of food, subsequent to a nuclear accident. The protocol outlines the food products to be analysed and prioritize the analysis based on the shelf life and market value. The methodology proposes use of a GIS based decision support system (GIS Web-DSS) where data can be visualized in terms of radioactivity and relative color-coding which can be understood by both the decision makers and by the people who are going to be affected by

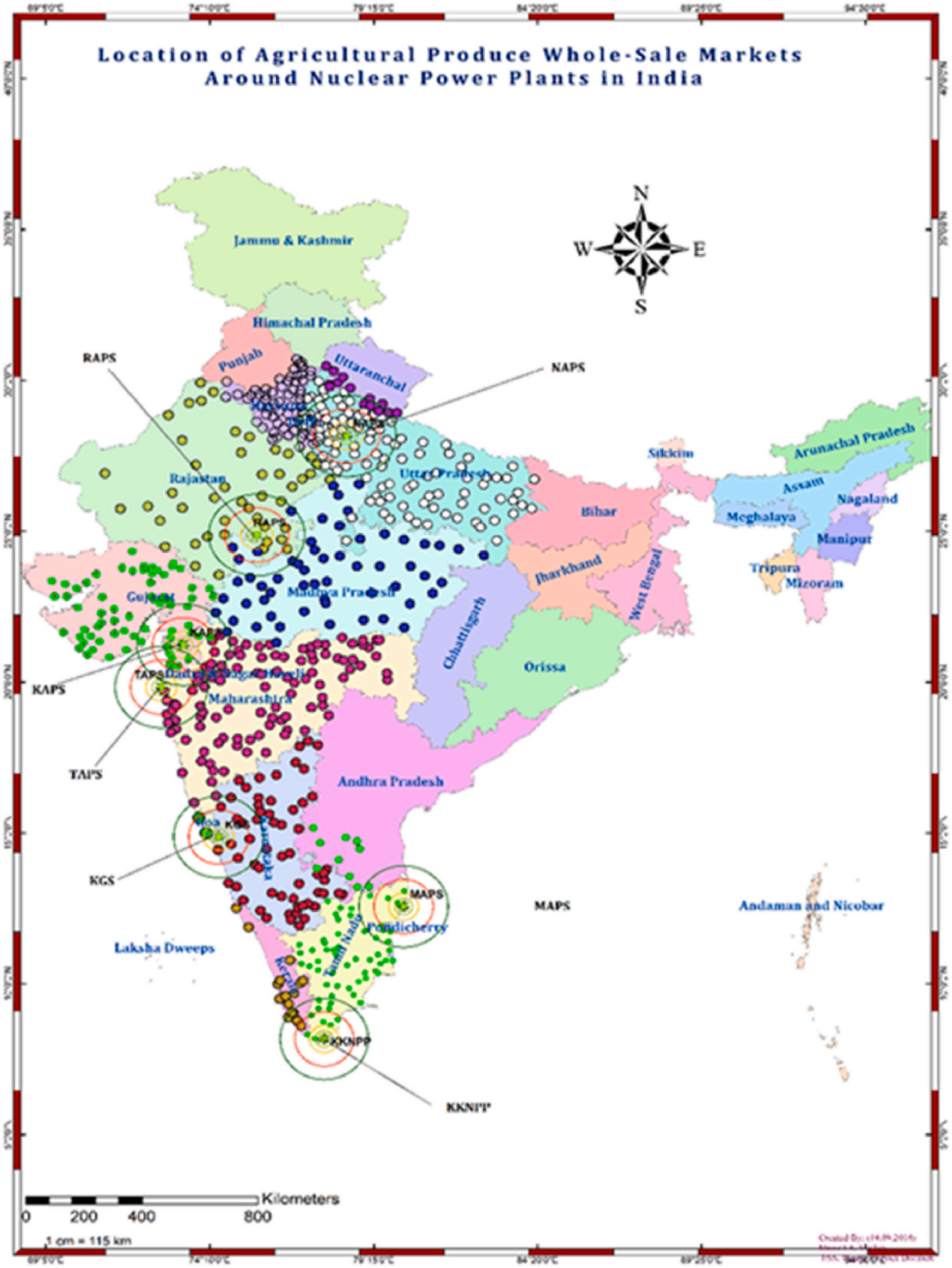

Fig. 8. Geo-tagged locations of Agro-product markets near NPPs which will be target location for speedy sampling of verity of agro-produces within short period of time.

the decision. This protocol is in line with the web-based decision-making system being developed by IAEA as part of on-going IAEA-CRP (Coordinated Research Project) on response to nuclear emergency affecting food and agriculture.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

AERB, 2018. Atomic Energy Regulatory Board, Annual Report 2018. Atomic Energy Regulatory Board. NIYAMAK BHAVAN, Mumbai.
AERB, 2014a. Site Evaluation of Nuclear Facilities, AERB Safety Code- [CODE NO.AERB/NF/SC/S (Rev.1)]. AERB, Mumbai, India.
AERB, 2014b. Criteria for Planning, Preparedness and Response for Nuclear or Radiological Emergency.
AERB, 2007. Regulatory Inspection and Enforcement in Nuclear Power Plants and Research Reactors (AERB/NPP/SM/G-1). Atomic Energy Regulatory Board, Mumbai.
Alexakhin, R.M., Fesenko, S.V., Sanzharova, N.I., 1996. Serious radiation accidents and the radiological impact on agriculture. Radiat. Protect. Dosim. 64, 37–42.
Alexakhin, R.M., Sanzharova, N.I., Fesenko, S.V., Spiridonov, S.I., Panov, A.V., 2007. Chernobyl radionuclide distribution, migration, and environmental and agricultural impacts. Health Phys. 93, 418–426.
APEDA, 2018. Annual Report of Agricultural & Processed Food Products Export Development Authority, first ed. APEDA, Ministry of Commerce & Industry, Govt. of India, New Delhi.
Banerjee, S., Gupta, H.P., 2017. The evolution of the Indian nuclear power programme. Prog. Nucl. Energy 101, 4–18.
Beresford, N.A., Fesenko, S., Konoplev, A., Skuterud, L., Smith, J.T., Voigt, G., 2016. Thirty years after the Chernobyl accident: what lessons have we learnt? J. Environ. Radioact. 157, 77–89.
Bhuyan, B., Sahoo, B.K., Suar, D., 2020. Food insecurity dynamics in India: a synthetic panel approach. Social Sciences & Humanities Open 2, 100029. https://doi.org/10.1016/j.ssaho.2020.100029.
Brandhoff, P.N., Bourgondiën, M.J., Onstenk, C.G.M., Avezathe, A., Peters, R.J.B., 2016. Operation and performance of a national monitoring network for radioactivity in food. Food Contr. 64, 87–97.
Census 2011, 2011. Census of India -2011 [WWW Document]. URL. https://www.census2011.co.in/. accessed 6.14.20.
Central Electricity Authority, M. of P, 2018. Power sector at a glance all India. In: Govermnet of India (Ed.), Power Sector at a Glance, Ministry of Power. Central Electricity Authority, New Delhi.
Cipollaro, A., Lomonaco, G., 2016. Contributing to the nuclear 3S's via a methodology aiming at enhancing the synergies between nuclear security and safety. Prog. Nucl. Energy 86, 31–39.
Codex-Alimentarius, I.F.S., 2006. Codex General Standard for Contaminants and Toxins in Food and Feed (Adopted in 1995), CODEX STAN193-1995 (Rev. 2015). Codex Alimentarius Commission. FAO & WHO, Rome.
eNAM, 2019. National agriculture Market| Success Stories [WWW Document]. URL. https://enam.gov.in/web/success-stories. accessed 6.12.20.
GOI, 2014. Production of Major Crops. Government of India.
GOI, M., 2020a. ECONOMIC SURVEY 2019-20: STATISTICAL APPENDIX.
GOI, N., 2020b. Open government data (OGD) platform India [WWW Document]. URL. https://data.gov.in/. accessed 6.18.20.
Goodchild, M.F., 2010. Twenty years of progress: GIS in 2010. Journal of Spatial Information Science 1, 3–20.
Haque, M.E., Gomi, T., Sakai, M., Negishi, J.N., 2017. Developing a food web-based transfer factor of radiocesium for fish, whitespotted char (Salvelinus leucomaenis) in headwater streams. J. Environ. Radioact. 172, 191–200.
Hegde, A.G., 1998. Environmental Radiological Laboratory Procedure Manual (Health Physics Division), second ed. ESL Manual. HPD, BARC, Mumbai.
IAEA, 2017. Operational Intervention Levels for Reactor Emergencies and Methodology for Their Derivation, Emergency Preparedness and Response-EPR-NPP-OILs. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna (ISSN 2518–685X).
IAEA, 2016. Criteria for Radionuclide Activity Concentrations for Food and Drinking Water (TECODC 1788), TECDOC Series. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna.
IAEA, 2015. In: Preparedness and Response for a Nuclear or Radiological Emergency (STI/PUB/1708), STI/PUB/1708. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna. General Safety Requirements Series.
IAEA, 2007. Arrangements for Preparedness for a Nuclear or Radiological Emergency. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna. Safety Guide (STI/PUB/1265), IAEA Safety Guide Series GS-G-2.1.
IAEA, 2002. Preparedness and Response for a Nuclear or Radiological Emergency Safety Standards: Requirements GS R-2 (2002). INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna. General Safety Requirements.
IAEA, 1997. Generic Assessment Procedures for Determining Protective Actions during a Reactor Accident. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna. TECDOC Series 955 (ISSN 1011-4289).
IAEA, 1989. Measurement of Radionuclides in Food and the Environment - A Guidebook (TRS-295). Technical Report Series-295 (ISBN-92-0-125189-0).
ICRP, 2012. The 2007 Recommendations of the International Commission on Radiological Protection: Annals of the ICRP – Publication 103 (ISSN 0146-6453). Elsevier-for ICRP, Sweden, ISBN -978-0-7020-3048-2.
INSAG, 1996. Defence in Depth in Nuclear Safety: A Report by the International Nuclear Safety Advisory Group (STI/PUB/1013). INSAG Series 10- ISSN 1025-2169. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, Austria, ISBN 92-0-103295-1.
Kirchner, G., Wirth, E., 2007. Operational Intervention Levels (OILs)– A Tool to Overcome Differences in Intervention Levels? Federal Office for Radiaiton Protection. Willey-Brandt-Strabe 5, Salzgitter, Germany, p. 38201, 7.
Konstantopoulos, S., Ikonomopoulos, A., 2015. A conceptualization of a nuclear or radiological emergency. Nucl. Eng. Des. 284, 192–206.
Kumar, S., Harikumar, S., Varghese, C.S., Shukla, D.K., 2017. Regulatory aspects of nuclear power program in India. Prog. Nucl. Energy 101, 146–159.
Kutkov, V.A., Tkachenko, V.V., 2017. Fukushima Daiichi accident as a stress test for the national system for the protection of the public in event of severe accident at NPP. Nuclear Energy and Technology 3, 38–42.
Lele, U., Goswami, S., 2020. Agricultural policy reforms: roles of markets and states in China and India. Global Food Security 26, 100371. https://doi.org/10.1016/j.gfs.2020.100371.
Mikami, S., Maeyama, T., Hoshide, Y., Sakamoto, R., Sato, S., Okuda, N., Demongeot, S., Gurriaran, R., Uwamino, Y., Kato, H., Fujiwara, M., Sato, T., Takemiya, H., Saito, K., 2015. Spatial distributions of radionuclides deposited onto ground soil around the Fukushima Dai-ichi Nuclear Power Plant and their temporal change until December 2012. J. Environ. Radioact. 139, 320–343.
NIN, 2011. Dietary Guidelines for Indians: A Manual, second ed. Indian Council of Medical Research, Hyderabad.
NPCIL, 2020a. Nuclear Power Corporation of India Limited [WWW Document]. URL. https://npcil.nic.in/content/297_1_ProjectConstructionStatus.aspx. accessed 6.11.20.
NPCIL, 2020b. Operational Nuclear Power Plants in India [WWW Document]. Nuclear Power Corporation of India Limited, Mumbai. https://www.npcil.nic.in/content/302_1_AllPlants.aspx.
Onda, Y., Kato, H., Hoshi, M., Takahashi, Y., Nguyen, M.-L., 2015. Soil sampling and analytical strategies for mapping fallout in nuclear emergencies based on the Fukushima Dai-ichi Nuclear Power Plant accident. J. Environ. Radioact. 139, 300–307.
QGIS, 2018. QGIS, supported data formats [WWW Document]. QGIS.org. https://docs.qgis.org/2.8/en/docs/user_manual/working_with_vector/supported_data.html. accessed 6.14.20.
Rajaram, K., Bhattacharya, N., Ramamurty, V., Madan, S., 2008. Geography of India, eighth ed. Spectrum Books (P) Ltd, New Delhi.
Saito, K., Mikami, S., Andoh, M., Matsuda, N., Kinase, S., Tsuda, S., Yoshida, T., Sato, T., Seki, A., Yamamoto, H., Sanada, Y., Wainwright-Murakami, H., Takemiya, H., 2019. Summary of temporal changes in air dose rates and radionuclide deposition densities in the 80 km zone over five years after the Fukushima Nuclear Power Plant accident. J. Environ. Radioact. 210, 105878. https://doi.org/10.1016/j.jenvrad.2018.12.020.
Saito, K., Tanihata, I., Fujiwara, M., Saito, T., Shimoura, S., Otsuka, T., Onda, Y., Hoshi, M., Ikeuchi, Y., Takahashi, F., Kinouchi, N., Saegusa, J., Seki, A., Takemiya, H., Shibata, T., 2015. Detailed deposition density maps constructed by large-scale soil sampling for gamma-ray emitting radioactive nuclides from the Fukushima Dai-ichi Nuclear Power Plant accident. J. Environ. Radioact. 139, 308–319.
Steiniger, S., Hunter, A.J.S., 2013. The 2012 free and open-source GIS software map – a guide to facilitate research, development, and adoption. Comput. Environ. Urban Syst. 136–150.
Team, Q.G.I.S.D., Q.G.I.S, 2018. QGIS Geographic Information System. Open Source Geospatial Foundation Project, 2.18.13 Las palmas, Boston.
WHO, 2011. Guidelines for Drinking Water Quality, fourth ed. World Health Organisation, Geneva.
Yamada, T., Kikuchi, M., Yagihashi, D., Yamakawa, S., Ishizu, H., Shiina, T., 2017. Screening test for radioactivity of self-consumption products in Fukushima after the Fukushima Dai-ichi NPP accident in Japan. Appl. Radiat. Isot. 126, 93–99.