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New paradigm for transforming Indian agriculture to climate-resilient and sustainable agriculture is a must

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ABSTRACT

Indian agriculture is the backbone of India's food, nutrition, and income security as well as sustainable growth. Indian agriculture is unique with 20 agro-eco regions, and 80 agro-eco sub-regions growing more than 100 crops in 1000,000 villages by 145 million farm-holders. India moved from *ship to mouth* situation in the late 1960s to food self-sufficiency and has become *Atmanirbhar* and an exporter of food by producing 316.06 million tonnes in 2020-2021. However, rural India needs urgent attention as there is a great divide between the urban and rural family incomes, and the primary sector's contribution to national GDP is hovering around 17-18% although the Indian economy is largely agrarian with 950 million rural population driving the economy. However, there is a large untapped potential in Indian agriculture to become the growth engine for the sustainable development of India as large yield gaps are existing. However, the challenges of growing water scarcity, increasing land degradation, growing population, urbanization, and most importantly impacts of climate change. Due to climate change with increasing temperatures, aridity is increasing in the country, and rainfall variability with a reduced number of rainy days and increasing intensity in different parts is a major concern. There is an urgent need to develop and adopt large-scale climate resilient management practices at a local level through empowering the small farm-holders with strengthened science of delivery using new science tools such as remote sensing (RS), global information system (GIS), internet of things (IoT), information technology (IT), artificial intelligence (AI), machine learning (ML), etc. Business as usual will not work and a new paradigm through building partnerships, enhancing collective action, market-led agro-eco region-based diversification and scaling-up through the empowerment of small farm-holders using new science tools is proposed. The government of India's action plan with 11 national missions is in place and all stakeholders need to contribute by enabling policies and sincere implementation for building resilience against the impacts of climate change.

Keywords: climate change, climate-resilient, sustainability, *atmanirbhar Bharat*, agriculture

CURRENT STATUS OF INDIAN AGRICULTURE

India has moved from the "*ship to mouth* "situation in the late 1960s to food self-sufficiency and has become *Atmanirbhar* and exporter of food, largely because of integrated efforts of our *Annadatas (*food Producers-Farmers), agricultural scientists, and policymakers. Food secure India with surplus food production produced 291.95 million tonnes of food grain production in 2019-20 and 316.06 million tonnes in 2020-2021 which is higher by 4.82 million tonnes (Ministry of Agriculture, Co-operation and Farmer Welfare, 2022). Even, during the COVID-19 pandemic, the agriculture sector showed resilience and our *Annadatas* enabled the country to see the first green shoots of the economy in the agriculture sector. Agriculture is on the right path, however, our *Annadatas* financial miserable situation is causing migration from rural areas to urban areas. In addition, the challenges to our food, nutrition, and income security are due to the growing population, growing water scarcity, and climate change impacts.

Rural India needs urgent attention for transforming the agrarian economy

Rural India comprises of a number of villages anywhere between 649481 according to Census, 2011 to 1000000 (MGNREGA) varying from 608,662 as per the Integrated

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Information Management System (IIMS) of the Ministry of drinking water and sanitation. The *Swach Bharat Abhiyan* (Gramin) report by the same ministry indicates 605,805 villages according to various government department databases as well as the definition (Rajeshvari Ganeshan, 2017). In rural India, agriculture is a primary sector providing a livelihood for 58% population of India, although, it contributes 17-18% to the national GDP. Although the Indian economy is largely agrarian as 950 million rural population (70% of the total population) drives the economy, the rural-urban divide is so prominent that the average rural income per capita per year (Rs 40,925) is less than half of the urban counterpart (Rs 98,435) in terms of net value added (NVA) as per the Ministry of Statistics and Project implementation (GoI, 2013, NSSO, 2013). Farmers in India are in distress as farming is not profitable and 55% of agriculture is rain-fed largely that depends on the vagaries of the monsoon and the uncertainties are further increased with climate variability and climate change impacts (Wani and Rockstrom, 2011). Thousands of farmers in different states committed suicides due to financial losses/crop failures, (11,772 in 2013, 12,360 in 2014, 12,602 in 2015, and 11,370 in 2016) (Das, 2011).

India is blessed with the largest arable agricultural land in the world followed by the USA and China enabling food security for 1.4 billion people with 314.51 million tonnes which is higher by 4.82 million tonnes in 2020-2021 (Department of Agriculture, Cooperation and Farmers Welfare, 2022) from 126 million ha under food grain cultivation. In spite of India's unique achievement in food production, India's food security position globally was 72nd as compared to the 3rd position for the United States of America, and the 35th position for China (Global Food Security Index, 2020). India has achieved self-sufficiency in cereals, pulses, milk but still imports edible oils. With increasing incomes food choices are changing and greater demand for fruits and vegetables is observed.

Challenges for sustainable agriculture and achieving food security

India has achieved food self-sufficiency for its growing population which is 1.4 billion at present (Wikipedia 2022a). However, the United Nations has projected that India may surpass China as the world's most populous country by 2023 instead of by 2027 as previously estimated as per the 2022 edition of the World Population Prospects (WPP). India's current population of 1.4 billion (UN-DESA, 2019) is projected to peak at 1.65 billion by 2060 (CBTE Database, 2021). With no room for agricultural extensification, the number of landholdings has surged to 146 M in 2015 from a modest 71 M in 1970 (Agriculture Census, 2019). In fact, 69% of the current landholdings are marginal farms (< 1 ha area) compared to 51% in 1970 suggesting that land fragmentation has continued possibly because of the prevailing socio-economic structure. With a strong linear correlation between population growth and the number of landholdings, smallholder farms remain the stark reality of Indian production systems (Das et al.2022). Such rapid strides in population in India have serious implications on water availability and particularly for food production as 80% of water withdrawals in India are for agriculture.

With the stagnant growth rate of 3.1 percent, achieving food, nutrition, and income security for the ever-growing population of India (1.46 billion by 2025 and 1.7 billion by 2050) remains a challenge (Government of India, 2017) as 55 percent of our agriculture is rain-fed. In brief, the challenges for India for sustainable development and food security in the 21st century are (Wani *et al*. 2018):

Climate variability and impacts of climate change

Growing population, urbanization, and increasing incomes

Large yield gaps with low crop yields

Water scarcity

Minimizing land degradation

Poverty elimination

CLIMATE VARIABILITY AND IMPACTS OF CLIMATE CHANGE ON AGRICULTURE

The constant increase in greenhouse gases concentrations, since preindustrial times, has led to positive radiative forcing of the climate, tending to warm the surface. Evidence over the past few decades has shown that significant changes in climate are taking place all over the world as a result of enhanced human activities in deforestation, emission of various greenhouse gases, and indiscriminate use of fossil fuels. For example, rise in atmospheric temperature by 0.74^{0} C over the last 100 years due to global warming and projected a temperature increase of 1.8 to 4^{0} C by 2100, global latitudes, especially in seasonally dry and tropical regions of the world as per the IPCC (Intergovernmental Panel on Climate Change) report (IPCC, 2007, 2018). The results of climate change research indicate that climate variability and change may lead to more frequent weather-related disasters in the form of floods, droughts, landslides, and sea level rise. Increased dryness and wetness in different parts of the country in the place of moderate climates existing earlier are observed in these regions. Climate change-induced changes in the cryosphere are also widespread, leading to a global reduction in snow and ice cover (Huss *et al*. 2017). Snow cover, glaciers, and permafrost are projected with high confidence to continue declining in almost all regions throughout the 21st century (IPCC, 2019). The accelerated melting of glaciers is expected to have a negative effect on the water resources of mountain regions and their adjacent lowlands, with tropical mountain regions being among the most vulnerable (Buytaert *et al*. 2017). Although the accelerated melting of glaciers may locally and temporarily increase streamflow, the reduction of glacier cover tends to lead to more variable river flows and reductions in base flow, while reductions in base flow in glacier-fed rivers are becoming evident in the Andes and the Himalayas (Walter *et al*. 2010). Such changes are likely to exacerbate water stress, which is among the main problems to be faced by many societies and the World in the 21st century. Future yields of rice, wheat, maize, and soybean will likely decrease significantly, by at least 25% in tropical and temperate regions as per the 5th Assessment Report of the IPCC (Porter *et al*. 2014). Global temperature increases of approximately 4^{0}C or more above late 20th century levels, combined with increasing food demand, could pose large risks to food security, both regionally and globally (John et al.

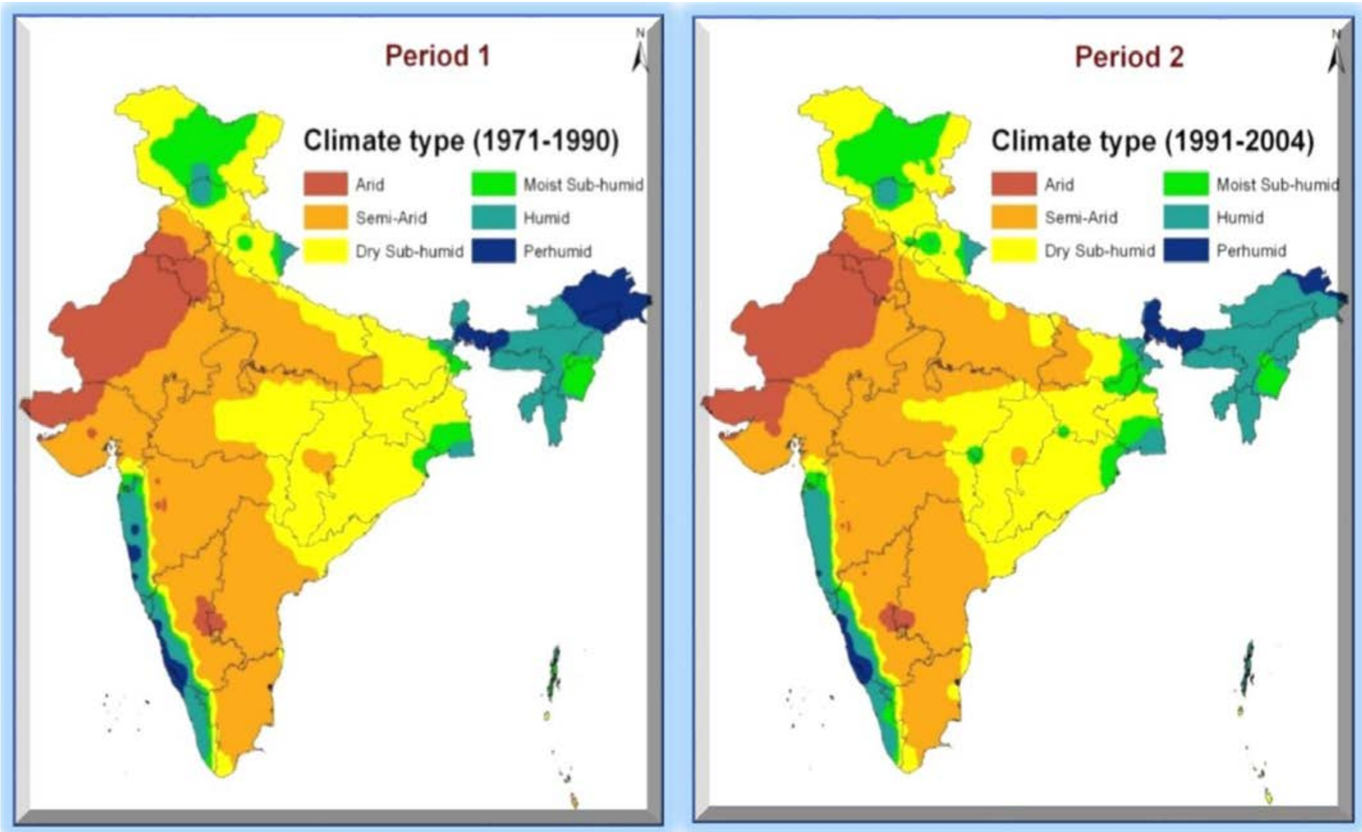

Fig. 1: Changes in agro-climatic regions in India due to climate change during 1971-1990 and 1991-2004). Source: Rao *et al.* (2013).

2020). At the international level climate change impacts are well established, however, there is an urgent need to assess the impacts of climate change at local (district and watershed) levels and develop suitable adaptation strategies for sustainable development.

In India, the number of rainy days during the season has decreased and rainfall intensities increased resulting in the frequent occurrence of dry spells during the crop growth period (Rao, *et al.* 2013, Fig. 1). In north India, irrigated wheat yields decreased as the temperatures increase and a 2^0 C increase resulted in a 17% decrease in grain yield, and with the further increase in temperature, the decrease in yield was very high (Aggarwal, 2008). So, the effect of climate change scenarios of different periods can be positive or negative for a given region depending upon the magnitude of change in atmospheric CO_2 and temperature. The highest decrease in chickpea grain yield per degree rise in seasonal *rabi* temperature was observed in Haryana (3.01 q ha^{-1}), followed by Punjab (1.81 q ha^{-1}), Rajasthan (1.27 q ha^{-1}), and Uttar Pradesh (0.53 q ha^{-1}) (Kalra et al. 2008). It was further indicated that due to climate change, there is a reduction in crop yield of 10 to 40% at the present yield level by the turn of the century. Changes in patterns and magnitudes of precipitation are also likely to affect rain-fed crop productivity and influence the availability of water resources for irrigation. Climate change is expected to exacerbate both the degree and incidence of high temperatures, thus negatively affecting major crops (John *et al*. 2020). Using an emissions scenario (Avnery *et al.* 2011) estimated that ozone-induced global yield reductions would be 10.6% for wheat, 4.3% for maize, and 12.1% for soybean by the year 2030.

Climate change is real and already at our doorstep, its implications are going to be borne by the poorest of the poor. Climate change will have a large effect on water globally which will vary regionally. This is due to spatially variable changes in precipitation, increased rate of glacier melt and retreat affecting river water flows, greater evaporation due to an increase in temperature, and higher water demand. These changes are likely to affect all aspects of agricultural water management including irrigation availability, soil moisture, evapotranspiration, and run-off (Boomiraj *et al*. 2010) as well as rainwater harvesting. Rain-fed agriculture economies are largely based on weather-sensitive agricultural production systems and are particularly vulnerable to climate change. This vulnerability has been demonstrated by the devastating effects of recent flooding and the various prolonged droughts during the twentieth century. Thus, for many poor countries that are highly vulnerable to the effects of climate change, understanding farmers' responses to climatic variation are crucial in designing appropriate coping strategies for climate change (Wani *et al*. 2010, Wani 2020). Increased semi-arid areas by 8.45 M ha in Madhya Pradesh, Bihar, Uttar Pradesh, Karnataka, and Punjab resulting in an overall 3.45 m ha addition to SAT (Rao *et al.* 2013 Fig. 1) is a concern as the areas affected are granaries of India. Dryness and wetness are increasing in different parts of the country in the place of moderate climates existing earlier in these regions. If the climatic change is accompanied by an increase in climate variability, many agricultural producers will experience definite hardships and increased risk due to reduced water availability and increased demand for irrigation.

For example, in a state like Karnataka in South India, which has a spectrum of climates ranging from per-humid type in the coastal and Malnad region to arid type in the Ballari-Vijayapura (Bellary-Bijapur) region, it was observed by Rao *et al*. (2016) that the south-west monsoon rainfall is likely to be more uncertain, with both increasing and decreasing trends in different parts of the state. Surface air temperature and diurnal temperature ranges are likely to increase along the high ranges of the Western Ghats and under such conditions there is a threat to thermo-sensitive crops such as black pepper (*Piper nigrum*), cardamom (*Elettaria cardamomum*), tea (*Camellia sinensis*), coffee (*Coffea* spp.), cashew (*Anacardium occidentale*) and other plantation crops. There are shifts in areas under different climates in the state. A study indicated shifts in rainfall peaks by 2–3 weeks in some parts of Karnataka influencing the time of sowing and subsequent crop growth, necessitating shifts in crops and cropping patterns to match the modified rainfall regime (Rao *et al.*2016). Several studies have clearly indicated that there is an urgent need to understand the impacts of climate change at the local level to benefit the farmers.

Growing population, urbanization, and increasing incomes

With the increasing migration of rural people to urban areas, the reduced contribution of agriculture and allied sectors to national GDP, the large income gap between urban and rural population, changing food habits due to increased incomes, and inefficient management of water resources are putting tremendous pressure on water demand in India. The World Economic Forum estimated that in India by 2030, 51% of the population adding 350 million individuals will be in the upper middle high-income and high-consuming category as compared to 24% in 2020 (World Economic Forum 2019). Increasing urbanization, shrinking farm size, development in education, and migration to cities in search of better livelihoods is increasing food demand. For example, in India with the growing population as well as increasing incomes more people are taking animal-based food and a shrinking number of vegetarian diet people (Table 1).

Large yield gaps with low crop yields (Untapped potential)

Currently, farmers' crop yields are low, particularly in developing countries in Asia, Africa, WANA, and Latin America with large yield gaps (0.5 to 5 t ha-1) based on the agro-eco region and the technologies used by the farmers (Rockström and Falkanmark, 2000, Wani *et al.* 2003a, & 2011, Bhatia *et al*., 2006 Rockström *et al*. 2010, FAO and DWFI, 2015, Anderson *et al*. 2016). Large yield gaps for rice (5.47 q ha-1), maize (12.77 q ha^{-1}), oil seeds, and field peas were reported in India (Beigh *et al*. 2015). Current rainwater use efficiency in dryland agriculture varies between 35% and 45% and the vast potential of rain-fed agriculture could be unlocked by using available scientific technologies, including improved cultivars. The vast opportunities existing in dryland areas can be harnessed for improving rural livelihoods (Wani *et al*., 2018).

Growing water scarcity

Water is one of the five eternal elements (namely, earth, water, fire, air, and ether) which are also known in ancient Indian literature "*Pancha maha bhuta*" is an elixir of life. Water is an essential part of the world's ecosystem and without water, life would be impossible. Historically, many of the early great civilizations, the so-called cradle of civilization like Mesopotamia situated between the major rivers Tigris and Euphrates; the ancient society of Egyptians depended entirely on the Nile; the Indus Valley civilization in India flourished along the once famous *Sarasvati* river. Water has always had a pervasive influence on the cultural and religious life of Indian people. The great bath of Mohenjo-Daro is a great testimony to this fact. The bath is considered by scholars as the "earliest public water tank of the ancient world" (Singh *et.al* 2020).

Meeting food demand for the growing population in tropical India with limited arable land and water resources is a challenge during the 21st century. During the 2011 census, India entered the league of water-deficient nations (below 1700 cubic meters per person) per year and India is amongst the most water-stressed countries. Per capita, water availability in 1951 was 5177 m^3 per year which has fallen to 977 cubic meters in 2010 and is expected to reach 802 cubic meters in 2022 and 677 in 2050 due to population growth (Table 2).

Table 1: Increasing population, water footprint and freshwater demand: Indian scenario.

Parameters	2010	2022	2050
Population in India (Million)	1150	1400	1660
Vegetarian percentage population	60 %	50 %	40 %
Vegetarian population (Million)	690	700	664
Non-vegetarian population (Million)	460	700	996
Daily water footprint for vegetarian diet, Liter/day	4500		
Daily water footprint for non-vegetarian diet, Liter/day	15000		
Annual water requirement for vegetarian diet (BCM)	1133	1149	1090
Annual water requirement for non-vegetarian diet (BCM)	2519	3832	5453
Total water requirement (BCM)	3652	4971	6543

Source: Derived from Water Demand in India in 2010-2050 by Sector-Statista 2021.

*Population used for 2022 is the actual population and for 2050 it is estimated by the UN.

Table 2: Water resources availability and demand in India.

Water Resources availability	2010	2022	2050
Estimated annual precipitation (including snowfall) (km^3)	4000		
Average annual potential in rivers (km^3)	1869		
Estimated utilizable water (km^3)	1123		
Surface water (km^3)	690		
Groundwater (km3)	433		
Existing surface storage (km3)	214	412	412
Population (Million)	1150	1400*	1660*
Per Capita water availability (m3)	977	802	677
Water demand in different sectors (BCM)			
Domestic	56	73	102
Irrigation	688 (84%)	910 (83%)	1072 (74%)
Industry	12	23	63
Energy	5	15	130
Others	52	72	80
Total	813	1093	1447

Source: Derived from Water Demand in India in 2010-2050 by Sector-Statista 2021.
*Population used for 2022 is the actual population and for 2050 it is estimated by the UN.

Water scarcity varies in different regions which could be physical scarcity, economic scarcity, or institutional scarcity. Physical water scarcity occurs when the demand of the population exceeds the available water resources of a region meaning when water is not abundant enough to meet all demands of the population. Physical water scarcity is often a seasonal phenomenon, rather than a chronic one and climate change is likely to cause shifts in seasonal water availability throughout the year in several places (IPCC, 2014). Globally about four billion people live under conditions of severe physical water scarcity for at least one month per year (Mekonnen and Hoekstra, 2016). Economic water scarcity occurs when water is adequate, but is unavailable due to a lack of significant investment in water infrastructure. Around 1.6 billion people, or almost a quarter of the world's population, face economic water scarcity, which means they lack the necessary infrastructure to access water (UN-Water, 2014).

India receives half of its annual rainfall in just 15 days making floods and drought a fact of life in the country. With an annual average rainfall of 1180 mm, India does not face a water crisis but it's the management of water resources calling attention urgently and particularly so in agriculture. Water stress is primarily a blue water issue, and large opportunities are still possible in the management of rain-fed areas, i.e., the green water resources in the landscape as per the Comprehensive Assessment of green and blue water (Rockstrom et al. 2009). Compared to the 6.5 billion global population facing blue water stress by 2050, only 0.27 billion will have water scarcity if both green and blue water are considered

Increasing land degradation

Diminished ability of the land to support soil functions or services required for sustainable intensification results in large yield gaps between potential yield and actual yield in farmers' fields (Wani, 2021). The land is the base for all primary production systems and is a non-renewable resource. Of late, domestic and industrial sectors are competing with agriculture for good quality land and water resources. The demand for food is increasing with the increasing population, urbanization, increasing incomes, shrinking farm size, development in education, and migration to cities in search of better livelihoods. More people in India are taking animal-based food while the population on vegetarian diets (which needs almost 1/3rd of water for producing the same calories in food) is shrinking. Increased food production has to come from the available, finite, and limited water and land resources that are declining in quality and quantity (Wani *et al*., 2011a, 2011b). Land degradation which is in existence in the past also, has become a serious problem worldwide as the pace of natural resource degradation has greatly increased in recent times due to the burgeoning population and the increased exploitation of natural resources. Global food systems are responsible for 80% of the world's deforestation, 70% of freshwater use, and contribute to 40% of the planet's degraded land, according to the latest report by the U.N.'s Convention to Combat Desertification (UNCCD). The cost to restore one billion degraded hectares (2.47 billion acres) of land by 2030 is estimated to be $300 billion annually. Investing in

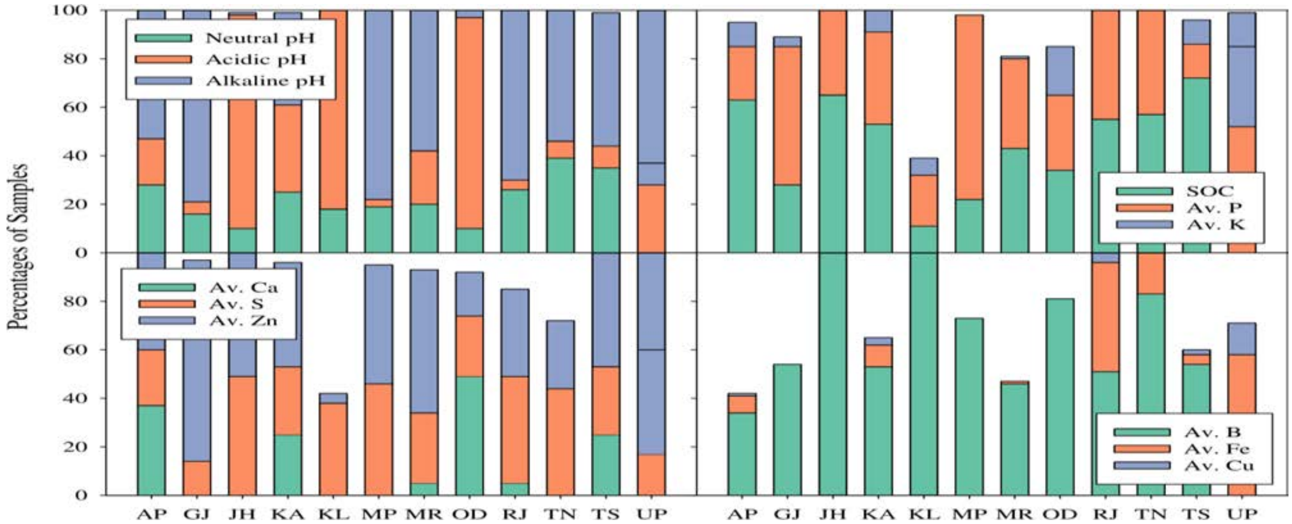

Fig.2: Percentages of soil samples showing different ranges of soil pH and deficiencies in soil organic carbon (SOC) and different nutrient contents in farmers' fields samples collected from selected states of India. (AP: Andhra Pradesh, GJ: Gujrat, JH: Jharkhand, KA: Karnataka, KL: Kerala, MP: Madhya Pradesh, MR: Maharashtra, OD: Odisha, RJ: Rajasthan, TN: Tamil Nadu, TS: Telangana, and UP: Uttar Pradesh). Source: Das *et al.(*2022)

restoration creates benefits that exceed the costs, says the report, as every dollar invested in restoration activities provides a $7-30 return in economic benefits (Global land outlook, 2022). The global experiences relating to land degradation highlighted the important degradation processes (loss of soil organic matter, soil physical degradation, nutrient depletion, chemical degradation, soil erosion and sedimentation, and degradation of landscape functions) that are closely linked to water use and management (Bossio et al. 2010). Some 97.85 million hectares — nearly 30 percent of India's land — underwent land degradation during 2018-19, according to Desertification and Land Degradation Atlas of India, released by the Space Applications Centre of the Indian Space Research Organisation. Land degradation has increased with irrigation availability resulting in erosion, salinity building, overuse of irrigation as well as run-off causing nutrient loss resulting in severe land degradation affecting productivity. Also inappropriate use of chemical fertilisers such as overuse of nitrogen, also use of di-ammonium phosphate in place of single super phosphate resulting in sulphur deficiency starting with soybean growing areas in Madhya Pradesh caused land degradation through nutrient depletion. Also, the emergence of secondary and micro-nutrients deficiency in rain-fed areas have caused and continues to cause land degradation in India. Soil health is severely affected due to land degradation and is in need of urgent attention. Often, soil fertility is the limiting factor to increased yields in rain-fed agriculture (Rego *et al.*2005). Soil degradation, through nutrient depletion and loss of organic matter, causes serious yield decline closely related to water determinants, as it affects water availability for crops, due to poor rainfall infiltration, and plant water uptake, due to weak roots. Nutrient mining is a serious problem in smallholder rain-fed agriculture. On-farm diagnostic work of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in different community watersheds in different states of India as well as in Southern China, North Vietnam, and Northeast Thailand showed severe mining of soils for essential plant nutrients including secondary and micronutrients along with macronutrients (Sahrawat *et al*. 2007, Fig.2). Land degradation reduces WUE at field and landscape scales and affects water availability, quality, and storage. Because of this strong link between land and water productivity, improving water management in agriculture requires that land degradation be mitigated or prevented.

Business as usual (BAU) will not work

An innovative, implementable, and scalable strategy for sustainable and climate-resilient agriculture which is a primary sector is urgently needed in India. Business as usual (BAU) will not work and Innovative policies and strategies for climate-resilient agriculture for *Atmanirbhar Bharat* must be developed and implemented earnestly to address the challenge of climate change impacts, growing water scarcity, increasing land degradation, and large yield gaps. Unfortunately, agriculture in India is an untransformed sector, plagued with compartmentalization, poor extension reach to small farm-holders, poor infrastructure for storage and transportation resulting in huge post-harvest losses and a large number of middlemen (long value chains) along with a lack of water use (rainwater, surface water as well as groundwater) policies resulting in a lot of wastage, inefficient use, and overexploitation of the finite resource. The COVID lockdown has aggravated the woes of our "*Annadatas*" further in addition to climate change (Singh and Wani, 2020). Current strategies for food production will not meet our demand considering the impacts of climate change, growing population, decreasing per capita water availability, and growing demand for water for food production due to increasing incomes, changing food habits and growing food demand (Table 1 & 2).

Urgent need to surpass "Death Valley of Impacts´

Large yield gaps for all the crops are observed in India inspite of the largest research network in the country and the availability of game-changing technologies with the researchers for increasing agricultural productivity, due to the existence of the Death Valley of impacts (Wani and Raju, 2018, 2020). do

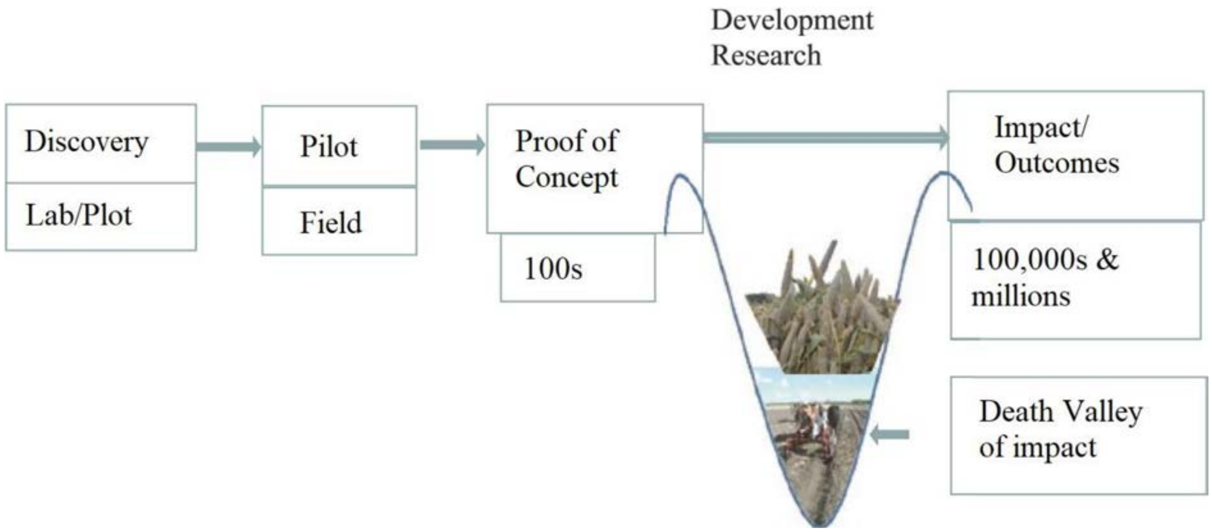

Fig. 3: Death Valley of impacts: Pictorial representation of the life cycle of technology/product. (Source: Wani and Raju 2016, 2020; Wani 2021)

not penetrate smallholder farms. A recent assessment of more than 100,000 articles by the CERES 2030 Team (Nature, 2020) suggests that it is smallholder farms are generally neglected while developing agricultural technology. The lack of a holistic approach to target system-level productivity, value-chains, and market linkages along with the impacts of climate change continue to affect small farm-holders (Wani and Raju, 2018; Wani *et al.*, 2018; Wani, 2021). Significant impacts of innovative technologies are not being realized possibly because of the so-called "Death Valley of impact" (Fig. 3), which results from the lack of synergy amongst different actors, a compartmental approach adopted by researchers, supply-driven technologies (rather than being demand-driven), and poor community participation (Wani and Raju, 2016, 2020; Wani, 2021).

The weak science of delivery in India is the main constraint to benefitting small farm holders from new technologies/products in the country. The existing extension system is not up to the mark as fifty-nine percent of farmers in India do not get any knowledge support (extension support) and current government machinery is supporting only 11 percent of farmers while the remaining 30 percent of the farmers get support from peers, media and private agencies (NSSO, 2013, GoI, 2013). Reddy (2018), Hans India (2018), and Sumanth, *et al*.(2020) highlighted the limited reach of the public extension, in addition, the extension system is burdened with non-extension responsibilities such as the distribution of subsidies and inputs, with little time left to attend to core extension activities like advising farmers to enhance adoption of new practices and techniques. The majority of farmers in India do not have access to any source of information; this lack of access severely limited their ability to increase productivity and income and reduce vulnerability (Glendenning *et al.* 2010). Lack of technical advice, inputs, and ideas, collectively known as extension services for the small farm-holders was identified by the Ceres 2030 researchers globally based on a meta-analysis of >100000 research papers and reports as the main constraint for the adoption of new approaches/ technologies/products. Small farm-holders are more likely to adopt new approaches — specifically, planting climate-resilient crops — when they are supported by technical advice, input, and ideas (Nature Food, 2020). Science needs to change its focus for crossing the Death Valley of impacts to achieve impacts (Nature Food, 2020) and scientists as well as research managers, extension staff, policymakers, donor agencies, publishers of the research journals, and farmers must change their mind-set (Wani and Raju, 2018, 2020). Awareness building and community participation which are driven by the tangible benefits for society through their demand-based solutions rather than supply-driven solutions can change the mind-set of people. Agriculture and staying in rural areas are considered no-choice options which need to be changed through the development of rural areas with the provision of urban facilities in rural areas (PURA) like initiatives. Change of mind-sets and seeking their participation is a challenge that has to be pursued vigorously and rigorously.

A NEW PARADIGM IS A MUST FOR ADDRESSING THE CLIMATE CHANGE

As reported earlier, BAU model won't work and there is an urgent need to transform Indian agriculture to become climate-resilient agriculture. We need to use new science tools like remote sensing, drones, artificial intelligence (AI), machine learning (ML), cloud computing, simulation modelling, global information system (GIS), and information and communication tools (ICT) tools like mobile, social media, etc. to reach millions of small far-holders (Wani and Raju, 2018, 2020, Wani *et.al* 2018, Dalwai, 2020, GoI, 2021, Wani, 2021). There is an urgent need to overcome the complexities of Indian agriculture. While providing solutions to the farmers the silos which are created with watertight boundaries need to be blasted through urgent reforms to enable the country to harness the power of the IT revolution. India is moving in the right direction for transforming agriculture in the country as evident from the number of initiatives and concept paper like IDEA (Indian Digital Ecosystem for Agriculture) by the government departments for transforming agriculture and new Farm Laws. Several states have digitized 90% of land records. Fortunately, India is in forefront of the IT revolution and the country must encash this opportunity by overcoming compartmentalization and holding of data which is the government's proprietary right. The Ministry of Statistics and Project Implementation need to be strengthened and work along with IT Ministry to collect, sanitize, organize, and develop protocols for data security, sharing, and use. Government reforms are in this direction, for example, the Ministry of Agriculture is named DOAC&FW, Ministry of Jal Shakti is newly formed by converging water-related activities of different ministries.

Agriculture in India is full of complexities with 20 agro-eco regions (AERs), 80 agro-eco sub-regions, growing 100 crops during three to four seasons in 29 states and 9 union territories. Further agriculture is a state subject and any advancement in agriculture becomes a challenging task for the central government. There is an urgent need for innovative and scalable policies across the country with the proper and honest implementation for sustainable climate-resilient agriculture. A holistic and integrated consortium approach for developing rain-fed areas sustainably for watershed development is recommended (Singh *et al.* 1998, Samra and Eshwaran 2000, Kerr 2001, Wani *et al.* 2003, 2011, Molden *et al*. 2007; Rockström *et al*. 2007, 2010, Dalwai 2020) and same can be employed for climate resilient agriculture in the country. The new paradigm for climate-resilient agriculture must be science-based using new science tools for providing integrated and holistic solutions to millions of small farm-holders. This calls for building partnerships with researchers, development agencies, private entrepreneurs, extension departments, and civil society organizations (CSOs) adopting a consortium approach.

In brief, the empowerment of small farm-holders is critical and to achieve this change of mind-set of all the actors is a must to ensure that small farm-holders become partners through community participation for adopting an integrated holistic value chain approach using new science tools (Wani *et al*.2018, Wani, 2021). Further, farmers need to adopt the" Fork to farm" approach based on the market demand instead of the minimum support price based ´Farm to fork" approach.

This has been understood by the central government and putting policies for green development across the country. However, much need to be done urgently, and state governments also must pursue a similar approach to sustainable development and for overcoming the challenges of climate change, water scarcity, income, and food security.

Efficient use of resources such as water, nutrients, sunlight, etc. is critical for harnessing the benefits through science-based interventions using new science tools. For example, in India, water and nutrient use efficiencies are currently hovering around 35-50% resulting in low crop yields. The government of India has taken up several steps towards misuse of resources (nutrients and water) through schemes like the Integrated Watershed Development Program (IWMP), *Pradhan Mantri Krishi Sinchai Yojana*, Soil health card mission, mandatory coating of all agricultural urea with an extract from neem cakes produced from neem trees (*Azadirachta indica*) to stop divergence of urea for industrial use (Wikipedia, 2022b) as well as enhances the NUE by 5 to 7% (Mangat and Narang (2004) through inhibiting denitrification and reducing the size of urea bag by 5 kg has gone a long way in enhancing NUE, reducing chemical use and increasing profits for the farmers. According to industry estimates, there could be savings of about ₹ 10,000 crores on account of lower use. Further, the use of Nanotechnologies for the controlled release of fertilizers can go a long way in doubling NUE. In India, already, Nanomaterials are being tested on a field scale for minimizing losses as well as for enhancing NUE. Nano-fertiliser uptake is more as fertilizers are loaded on nano-particles which enter the plant cells and work at the cellular level. Nano fertilizers can be applied either by spraying or soil application and compared to chemical fertilizers requirement and cost, nano-fertilizers are economically cheaper and are required in a lesser amount. India which is the largest importer of urea and DAP is eying self-sufficiency in urea through the production of a locally developed version of nano-urea in six plants by 2024-25 overcoming the import of 20 million tons of urea saving 40,000 crores INR annually (Hindustan Times, 2022) using the technology developed by Indian Farmers and Fertilisers Cooperative (IFFCO).

Enabling Innovative, Implementable, and Scalable Policies for Sustainable climate resilient Agriculture.

For the success of any initiative/program enabling policies at a macro-and micro-level as well as enabling institutions and proper implementation, monitoring, and learning are very much needed. Policy-makers around the world face common challenges: improving coherence between sectoral policies, balancing economic growth with social, environmental, and climate action, and using resources more efficiently and effectively. A common ground for compromise needs to be found to effectively address trade-offs between development and environmental protection, and also between the diverging interests of the various economic sectors. At the same time, applying a nexus approach can bring mutual benefits between, among others, energy, agriculture, ecosystems, and water efficiency (IRENA, 2015). The best example of Watershed management in India clearly demonstrated that the watersheds which started as a drought-prone area program (DPAP) by the central government in close integration with the state governments evolved through common guidelines by the government of India. Through evolving watershed guidelines this program transformed from soil conservation, and rainwater harvesting to water harvesting, efficient water use, and soil conservation to livelihood improvement through a number of revisions in watershed guidelines (Wani *et al*.2008a).

Similar was the case for many successful scaling-up programs such as *Bhoochetana* and *Bhoo Samrudhi* in Karnataka, *Rythu Kosam* in Andhra Pradesh, and several corporate social responsibility (CSR) projects (Wani, 2021). The government of India is actively pursuing the transformation of agriculture and a basket of new reforms to promote value-chain development as well as marketing at national and international levels. New reforms such as the creation of Gramin Agricultural Markets (GrAMs) as aggregation platforms, opening up of three market channels viz. APMCs, intra and interstate direct trade under The Farmers Produce' Trade and commerce (Promotion and Facilitation) ordinance, 2020, Agricultural Export Promotion Policy 2018 focussing on volumes, standards & quality and cluster approach to production, liberalization of control orders under The Essential Commodities Act,1955, contracts in respect of farming and services through Farmers (Empowerment and Protection) Agreement on Price

Assurance, Kisan rail and air flights, Farm Services Ordinance, 2020, and Promotion of 10,000 FPOs. Under *Atmanirbhar Bharat* which targets an investment of 1.65 lakh crore in the farm sector, Agri. logistics will get a boost across all sectors. For rural transformation, proper implementation is very critical and a must. Awareness building amongst the public and making it a public movement through active participation, DBT, implementation through an online process, and removing intermediaries who generate corruption. As indicated earlier, there are no policies for sustainable water use in agriculture, AESR- market-based agriculture (fork to farm) instead of MSP-based agriculture (farm to fork), and shifting agriculture to a business model rather than subsistence agriculture in India. Such enabling policies and associated institutions would help the scaling-up of integrated holistic solutions for the farmers and transform the rural sector through a new paradigm.

STRATEGIES FOR CLIMATE CHANGE IN INDIA

India is committed to the UN Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, which represent the international consensus on the way to deal with climate change. It has a very comprehensive framework of legal and institutional mechanisms in the region to respond to the tremendous challenges to the environment it is facing, owing to population growth, poverty, and illiteracy augmented by urbanization and industrial development and has initiated several climate-friendly measures, particularly in the area of renewable energy. India adopted the National Environment Policy 2006 and has also taken many other measures and policy initiatives (Vipin Chandra and Sandhya, 2016).

India has, for many years, large nationally funded programs for reducing the adverse impacts due to natural climate variability. These programs need to be extended and enhanced to cover the additional risks of climate change, through the provision of financial resources and relevant technologies. Currently, several social sectors and development schemes that emphasize livelihood security, the welfare of the weaker sections, and rural infrastructure are under implementation. The Government of India also set up an expert committee to study the impact of climate change on various sectors on May 7, 2007. The committee has studied the impact of anthropogenic climate change on India and has come out with its first set of findings and the research agenda that the ministries need to follow and implement in order to address India's vulnerability to anthropogenic climate change impacts (Vipin Chandra and Sandhya, 2016).

Both mitigation and adaptation are needed to significantly reduce the risks and increase the resilience of the world's most vulnerable citizens. Adaptation and mitigation should not be considered as either/or strategies, but rather as complementary ones that should be pursued together. Several GoI policies and schemes significantly address adaptation objectives. The government of India has set up an 'Expert Committee on the Impacts of Climate Change to identify the measures that India may have to take in the future in relation to addressing vulnerability to anthropogenic climate change impacts. The National Action Plan on Climate change, prepared under the guidance and direction of the Prime Minister's Council on Climate Change, reflects the importance the Government attaches to mobilizing our national energies to meet the challenge of climate change. The National Action Plan focuses attention on 8 priority National Missions (Vipin Chandra and Sandhya, 2016). Seeking to expand its activities in different sectors to achieve the country's updated climate action targets, the government has decided to add three new 'missions' — on coastal ecosystem, human health and sustainable transport in addition to the eight missions (Jawaharlal Nehru National Solar Mission (JNNSM), Energy conservation and efficiency, National Mission on strategic knowledge for climate change (NMSKCC), National mission for sustaining Himalayan ecosystem, National Water Mission, Green India Mission, National mission on sustainable habitat (NMSH), National Mission for sustainable agriculture) to implement its existing National Action Plan on Climate Change (NAPCC), taking the total number of such dedicated missions to 11 (Visva Mohan, 2022).

Renewable energy solutions- including clean energy for homes, communities, solar and wind water pumps and clean and efficient household solutions for cooking and heating The following is the installed capacity for Renewables: Wind power: 41.2 GW, Solar Power, 59.34 GW, biomass/Co-generation: 10.2 GW, Small Hydro Power: 4.88 GW, Waste to Energy: 0.47 GW, Large Hydro: 46.85 GW. India has set a target to reduce the carbon intensity of the nation's economy by less than 45% by the end of the decade, achieve 50% cumulative electric power installed by 2030, and achieve net-zero carbon emissions by 2070. India has been ranked among the top 5 countries in the world, and the best among the G 20 countries, based on its Climate Change performance. India jumps 2 spots higher, and is now ranked 8th as per Climate Change Performance Index (CCPI, 2023) (Arora,2022).

For agriculture, we need to adopt sustainable land, water, and crop management practices to ensure the efficient use of resources for enhancing productivity. For minimizing land degradation, we need to adopt strategies for carbon sequestration through different cropping systems including legumes, the addition of organic manures, green manuring, mulching, suitable land, and water management practices and measures to enhance green water use efficiency in agriculture (Wani, 2020,2021, Wani and Raju,2018, 2020). For reducing poverty in rural areas we need to strengthen collective action through strengthening farmer-producer organizations (FPOs) as promoted by the GoI. There is an urgent need to strengthen market-led agro-eco region-based diversification by adopting the "*fork to farm*" approach instead of the "*farm to fork*" approach currently adopted by the farmers since the green revolution days. Now our country has moved from "*Ship to mouth*" situation to a surplus food producer and exporter (Wani, 2020, 2021, Wani and Singh, 2021).

CONCLUSIONS

Indian agriculture is unique with the largest arable land in the world cultivated by 145 million farmers in 20 agro-eco regions and 80 agro-eco sub-regions growing >100 crops during three-four seasons. However, there is a wide gap in family incomes between rural and urban families. Further, growing population, water and land scarcity exacerbated with impacts of climate change which is already at the doorstep are the challenges for food security, nutrition security, and sustainable livelihoods. To address the challenges of climate change we need to understand the effects of climate change at a local level and adopt resilient technologies through the empowerment of the small farm-holders. Along with sustainable agriculture through an integrated, holistic, and partnership-based approach using new science tools for empowering the farmers, there is an urgent need to ensure the provisioning of urban facilities like medical, education, power, sanitation, etc. in rural areas through (PURA) to check migration to urban areas. Adaptation and mitigation measures for climate change are essential and GoI's 11 missions need to be strengthened through enabling policies and sincere implementation to harness the potential of Indian agriculture to become the growth engine for sustainable development. Business as usual will not work and farmers need to adopt a "*fork to farm"* approach in place of the existing ´*farm to fork"* approach along with market-led agro-eco region-based diversification and value chain approach through collectivization for saving water, energy, and land for sustainable development by harnessing the power of new science tools.

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