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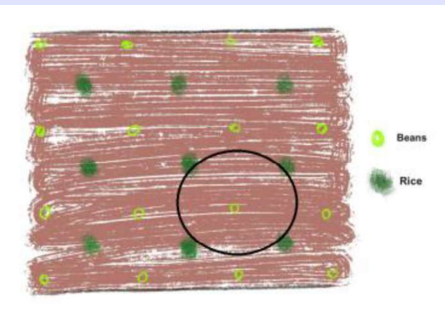


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# Agroecological engineering interventions for food security and sustainable rural development: The case of rice farming in Kashmir

Tavseef Mairaj Shah

2021

**This book is based on an updated and abridged version of the dissertation submitted in partial fulfilment of the requirements for award of the academic degree**

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**Tavseef Mairaj Shah**

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Doctoral Examination Committee:

I. Prof. Dr. Kerstin Kuchta, Hamburg University of Technology (Chairperson)

II. Prof. Dr. Ralf Otterpohl, Hamburg University of Technology (First Examiner)

III. Prof. Dr. Christoph Ihl, Hamburg University of Technology (Second Examiner)

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Institut für Abwasserwirtschaft und Gewässerschutz
Eißendorfer Straße 42
21073 Hamburg

Website: www.gfeu.org
Email: info@gfeu.org
Tel.: +49 (40) 42878-3207
Fax: +49 (40) 42878-2684

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Author ORCiD: https://orcid.org/0000-0002-7506-6739



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*For Ammi-jan and Abu-ji*

*"Shall the reward of good/kindness be anything but good/kindness?"*

## Abstract

The challenges faced by the food systems of our times are manifold—resource intensive farming, decreasing quality of food, unequal distribution of food and income, and waste. Input-intensive agriculture, dependent on industrially manufactured mineral fertilizers and pesticides, has skewed the socio-economic balance against the main growers and caretakers of food i.e. the farmers. Taking into consideration the ecological consequences of modern industrial agriculture, and the pace at which the principal natural resources vital for food—soil and water—are being exhausted irreversibly, the idea of a sustainable food system looks difficult to realise. Despite producing food enough for more than 8 billion people, we still have more than one-quarter of the world population living either in hunger or with improper nutrition. The coronavirus COVID-19 pandemic has served to further put light on the discrepancies of the food system as well as the socio-economic system. In a communique released in 2020 regarding the pandemic, the International Panel of Experts on Sustainable Food Systems (iPES Food) termed the crisis as an opportunity to rethink the world food systems and hence called for an urgent shift from industrial agriculture to diversified agroecology-based agriculture.

Water is one of the primary natural resources that are needed across all farming systems, albeit in differing quantities. Among the major food crops of the world, rice is classified as a 'thirsty crop' because of the large quantity of water that is used in the currently dominant form of flooded rice cultivation. Rice is the staple food for more than half the world population and is hence critical to food and nutritional security around the world. Rice farming system in the current dominant form of agrochemical-based flooded monocropping is however associated with ecological degradation in the form of water scarcity, pollution and soil degradation. With the food needs of the population expected to increase in the coming decades, a rethink and restructuring of the farming system looks imperative from an environmental and ecological engineering perspective. This study is a contribution in this direction. The first part of this work makes the case for agroecological interventions in agricultural systems, with a focus on rice farming systems (in South Asia). This part highlights the importance of rice as a world food as well as the role agroecology-based rice farming can play in mitigating bulk of the negative effects our current food systems have on the environment in the form of greenhouse gas emissions, water contamination, soil degradation, and loss of nutrients. The contribution of agriculture and rice cultivation to the regional GDP and employment is also discussed in the South Asian context. The potential contribution of agroecology towards the achieving of Sustainable Development Goals (SDGs) has also been discussed in this regard.

The second part of the work summarises the results of experimental studies of agroecological engineering interventions in rice farming done at laboratory and field level. The interventions dealt with an innovation to an existing agroecological methodology of growing rice called the System of Rice Intensification (SRI). The intercropping of legumes (beans) with rice grown under SRI was examined in this study. The hypothesis that intercropping can address two main reported drawbacks of SRI, which are weed infestation and increased labour, while improving the performance of the rice crop at the same time, was proven right in view of the results of the lab scale (greenhouse) experiments and the field experiments. In the experiments the water saving potential of SRI in comparison to the conventional flooded rice (CFR) cultivation, with

water savings of up to 39%, was also evidenced. In terms of plant growth characteristics, the number of tillers in rice plants was found to be multiple times higher in SRI as compared to CFR. In field experiments, the number of tillers was 3 times higher in SRI and the intercropping treatment. The new rice farming system based on the SRIBI (System of Rice Intensification with Intercropping) methodology is termed as Rice iCrop.

Intercropping was found to have significant effect on weed infestation in rice under SRI management and also led to an improvement in different plant growth characteristics and nutrient uptake of the plants. The nitrogen uptake in the rice plants was found to be 8% higher under intercropping regime, while as the chlorophyll content was found to be up to 40% higher as compared to SRI. The effect on the plant height under intercropping regime was very significant, with a 20% increase observed. The most significant result however was the reduction in the weed infestation observed with intercropping. The weed population in Rice iCrop reduced by 65% on an average in experiments over two years, with 77% decrease observed in 2019 and 59% in 2020, as compared to the SRI weedy control, with no weeding done in either treatment after the date of intercropping. The occurrence of blast disease was not observed in either SRI or SRIBI, which is otherwise a regular feature with the local variety of rice that was used in the experiments. The rice yield increased by 15-20% in the intercropping treatment as in 2019 and by 33% in 2020 field experiments. A significant increase in the fodder/rice husk yield was also observed, with a 70% increase in 2020. From the perspective of economics, the Rice iCrop system led to a 57% increase in the net earnings of the farmers, with the productivity increasing from 2.88 to 3.11.

Rice iCrop is proposed as an alternative rice farming system, introducing more agroecology to the System of Rice Intensification. It is a cropping system having the necessary adaption, resilience, and regeneration potential to cope up with the current challenges faced by the food system. This system is also beneficial from a socioeconomic aspect in that it contributes to diversifying the income of small farmers while reducing their dependence on external inputs at the same time. The results part of work ends on an anthropological note, with the recorded experiences and remarks made by farmers during the course of the field experiments included in the results. A decision support model is also included, aimed at benefitting farmers, facilitators, and researchers in future studies.

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## List of Abbreviations

AWD – Alternate Wetting and Drying

BlWSI – Blue Water Sustainability Index

CAWMA – Comprehensive Assessment of Water Management in Agriculture

CFR – Conventional Flooded Rice

CGIAR – Consultative Group for International Agricultural Research

DAT – Days after transplantation

EU – European Union

EC – European Commission

FAO – Food and Agriculture Organisation

FAOSTAT – FAO Statistical Database

GDP – Gross Domestic Product

GI – Geographical Indicator

GIZ – Gesellschaft für Internationale Zusammenarbeit

GRiSP – Global Rice Science Partnership

IAASTD – International Assessment of Agricultural Knowledge, Science and Technology for Development

IFAD – International Food and Agricultural Development

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPES-Food – International Panel of Experts on Sustainable Food Systems

ITPS – Intergovernmental Technical Panel on Soils

IWMI – International Water Management Institute

OECD – Organisation for Economic Cooperation and Development

SCI – System of Crop Intensification

SDG – Sustainable Development Goals

SMC – Soil Moisture Content

SRI – System of Rice Intensification

SRIBI – System of Rice Intensification with Beans Intercropping

SNPP – Spikelet number per plant

UN – United Nations

UNFCCC – United Nations Framework Convention Climate Change

# 1. INTRODUCTION

*"...so that you may be mindful [of Him] who spread out the earth for you and built the sky; who sent water down from it and with that water produced things for your sustenance."*
*– M. A. S. Abdel Haleem, English Translation of The Qur'an, 2016*

*"We can teach philosophy by teaching farming, but we cannot teach farming by teaching philosophy."*
*– Bill Mollison, 'Father of Permaculture'*

*"Am Anfang aller Humanität steht das Wasser. Am Anfang aller Würde, aller Gesundheit, aller Bildung, aller Entwicklung."*
*– Erik Orsenna, Die Zukunft des Wassers, 2008*

Food and farming systems play a major role in sustainably tackling the modern day challenges of resource degradation and economic disparity. In this regard, it is not surprising that most of the UN mandated sustainable development goals (SDGs) relate to food and farming systems one way or the other. A transition to resilient and sustainable food systems is hence essential to the fulfilment of these goals. With the current food production system, planetary boundaries are being challenged, and exceeded, in many ways and there is an urgent need for a transformation with a systems-approach. Otherwise, the large external (ecological) costs of our food production under the current model, which are not visible or stated when we buy our food at a supermarket, have to be paid by the human society at large in the foreseeable future. This book addresses this approach and is based on the doctoral research done at the Rural Revival and Restoration Engineering research group in the Institute of Wastewater Management and Water Protection at Hamburg University of Technology (TUHH), Hamburg, Germany[1].

On a European level, the ecological costs of food production are really tangible, in number reported in literature. The use of synthetic fertilizers has been found linked to the increased load (50-80%) of nitrogen in freshwater bodies, which negatively effects water quality and aquatic ecosystems. Agricultural intensification is associated with a rapid decline in on-farm biodiversity and soil degradation. Annually, 970 million tons of soil are lost in Europe as a result. In terms of climate change, the current agricultural model is a driver of the emission of stored carbon in the soil into the atmosphere. Agricultural production of food, fibre, and fuel accounts for 11.3% of greenhouse gas emissions and for 94% of ammonia emissions in the EU that worsen the air quality. Unsustainable food systems also have a negative effect on the social and health aspects of the society, giving rise to challenges like malnutrition and food poverty.

Around 10% of the European population was unable to afford a good quality meal every second day, in 2016. At the same time, more than half of the population is over-weight while as more than one-fifths of the population is obese. As a result, 70-80% healthcare costs in the EU are accounted by diet-related chronic diseases and the diet –related burden of cancer deaths stood at 35% in the United States [2–4].

## 1.1. Agreoecology and sustainability

Environmental degradation and resource scarcity are the issues environmental engineers counter through various means and interventions worldwide on a daily basis. In the current times, however, there is an added dimension to this problem in the form of changes in the global weather patterns and the increasing frequency or visibility of extreme weather events broadly classified under the umbrella of climate change. This has led to a paradigm shift in which environmentalists and ecologists are coming together in structuring the solutions to the new age problems. Any solutions to the problems in the environment need to consider the ecological interactions between different constituents in order for the solutions to be sustainable and acceptable to the primary stakeholders—the people!

This paradigm shift has resulted in a change of perspectives related to the questions of sustainability. Even in academic circles, a new line of thinking or a new field of studies—ecological engineering—has taken birth as a result of the new approach. If environmental engineering is the use of engineering methods to make positive changes or reverse negative changes in the environment, ecological engineering is the utilization of engineering together with the knowledge of ecological interactions to make a sustainable change in the various ecological systems. This work views the problems of water scarcity, soil degradation, and food inequality from this perspective and proposes solutions through the application of agroecology.

Agroecology is broadly classified as "the science of applying ecological concepts and principles to the design and management of sustainable food systems" [5]. It follows the approach of seeing the food production system i.e. agricultural system as a system in a constant interdependent relationship with other ecological systems. Agricultural systems cannot work on its own, independently, and any intervention in the food production system that does not take into the consideration its ecological relationships with other systems has less chances of being sustainable and healthy. Like in the three pillars model of sustainability where every section is viewed as equally contributing to sustainability and hence equally considered, without any preference. However, the preferential model of sustainability, which is the one that is being followed lately, takes into consideration the relationships and the interdependencies of the three systems—ecological, social, and economic. The slogan being: no economy without social considerations; no society without ecological considerations. So, in this model the ecological considerations have preference over the other two.

In the preferential model, agriculture plays a cross-sectorial role, as visualised in Figure 1. It has relationships with the different constituents of the ecological systems in terms of dependencies as well as influencing and being influenced by the ecological system. Soil, water, and air form the three main realms of ecology and agriculture functions when the three are in balance. And in turn, agricultural practices have an effect on the quality of these three constituents of ecology. The socio-economic face of agriculture is more tangible yet mostly invisible at the decision making stages and platforms. Agriculture is responsible for the livelihoods of more than half the world population while as more than 90% of all agricultural farms worldwide are family-farms or smallholder farms [6]. And it is mainly these smallholder farms that feed the overwhelming majority of the world population. In the economically poorer regions of the world, agriculture continues to be the major means of livelihood for the overwhelming majority of the population, for example in South Asia, more than 55% of the population earns livelihood through agriculture, directly or indirectly [7]. Food production systems, in the form of smallholder farmers, hence play a major role in the socio-economic setup worldwide, by steering the local and regional economies as well as avoiding chaos and conflict by ensuring the right supply of food. Agroecology advocates keeping a consideration of these relationships and interdependencies while making changes to the food production system.


*Figure 1. The three pillars model of sustainability (left) and the preferential model of sustainability (right); Agriculture as a part of the preferential model. (Licence: CC-BY-SA 4.0)*

The conventional initiatives of catering to increases in food demand through expansion of agricultural land by the conversion of non-agricultural land like forest or grasslands, or by the intensification of agricultural practices on existing land has contributed to environmental degradation in the past decades. This includes the depletion and contamination of water sources, soil degradation and depletion, disruptions to the biogeochemical cycles of earth, as well as contributions towards greenhouse gas emissions [8]. This is where the role of environmental and ecological engineers becomes relevant. This becomes more expedient in view of the effects that intensive industrial agriculture has on the financial situation of farmers worldwide as well as on the global food security, which paradoxically have been reported to have seen pervasive reductions despite increased food production rates that have no precedents in history [8].

The study of the ecology of agricultural systems is essential to solving the problems that our food production systems face. That agricultural activities have been described as the dominant ecological force over one-third of the land areas of the earth and their direct influence on the water quality points to the importance of ecological engineering in the area of agricultural systems. Different plant functional traits have either a strong predictive power of ecosystem response to environmental change or themselves have strong impact on ecosystem processes. Their study hence is important for tackling large scale ecological questions. Based on international consensus, 28 such functional traits have been termed as critical to this study of vegetation responses to and vegetation effects on, environmental changes [9]. Agroecological research based on these functional traits has been discussed as the possible framework that would allow the development of generalized hypotheses relevant for engaging with ecological questions at various levels: from farm-scale agricultural management, regional-level land-use planning, or an international environmental policy [8].

Trait-based agroecology is a relevant approach in this regard. It is the study of ecologically meaningful characteristics of plants and plant parts that are most important in “mechanistically predicting plant responses to, and impacts on, surrounding environments. Trait-based ecology is being embraced as a critical means by which scientists can test hypothesis on, and recommend management practices for terrestrial ecosystems. Trait-based agroecology employs a systems-approach to agroecosystems, in contrast to the vast amount of scientific and informal on-farm research that tends to focus mostly on yield and related functional traits. The systems approach seeks to understand the relation between functional traits and trait diversity, and multiple critical ecosystem functions, including yield, with the aim of predicting, managing and enhancing the functions (Figure 2).

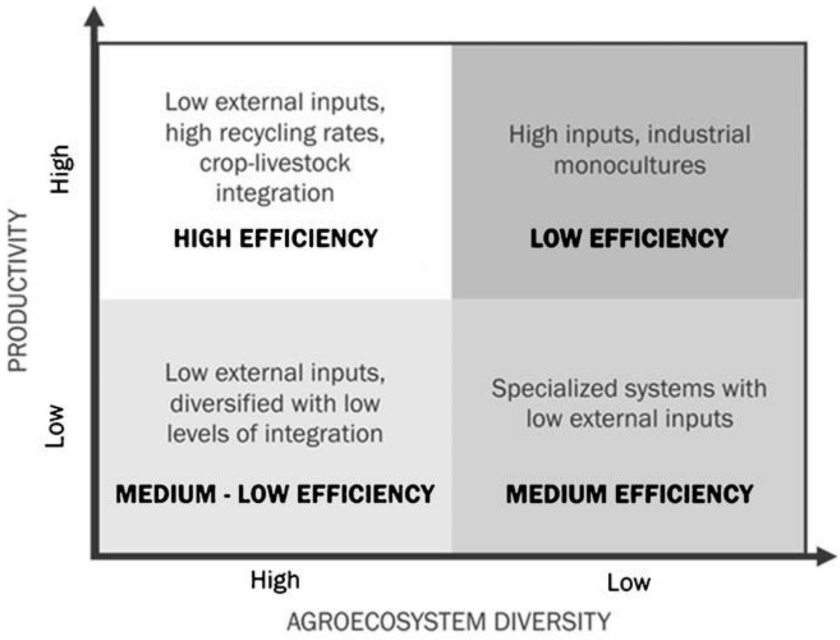



*Figure 2. Features of the green agro-ecosystems of the future (Funes-Monzote 2009)*

## 1.2. Water scarcity and its socio-political implications

Water has been touted as "the petroleum of the next century" or 'blue gold' and it follows as a consequence that food is the fuel of this century. It is the most important resource in the hotspots of world politics. Although there are many reasons behind the stirring armed conflicts worldwide, but water has the potential to be the necessary spark for a big fire, as seen recently in Syria and Yemen; in Syria, Daraa; in Yemen, Taiz. Although water issues alone have not been the sole trigger for warfare in the past, tensions over freshwater management and use represent one of the main concerns in political relations between riparian states and may exacerbate existing tensions, increase regional instability and social unrest [10](Figure 3).

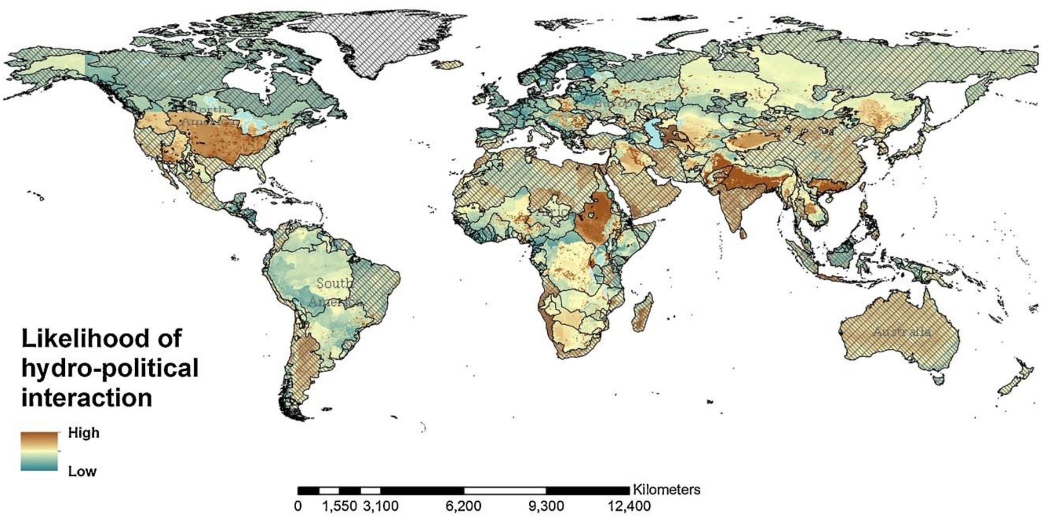



*Figure 3. The risk of potential international conflicts arising out of water scarcity (Farinosa et al., 2018)*

Water based conflicts have increased in frequency over the last few decades. It could be argued that population increase is the main reason, however it is not only that. The overall consumption per capita has drastically increased in this time. And a major portion of the total consume is the proportion of water that is consumed 'unconsciously'. This is the water that is not visibly consumed by individuals, in that it is neither consumed as a drink nor with food, and also not in washing or cleaning. This is the water that is known as virtual water, leading to the concept known as water footprint. The water footprint gives the total amount of water for a process, for example the agricultural process of growing rice. The total water footprint of a product is a sum of three constituent water footprints—green, blue, grey. Green water footprint is the water from precipitation that gets stored in the soil and is either incorporated by the plants or lost to the air through evapotranspiration. Blue water footprint is the water that has been withdrawn from surface waters or groundwater resources. Used for irrigation, this water is either lost to air through evapotranspiration, or seeps down into the soil, or is incorporated by the plants. Grey water footprint denotes the amount of freshwater required to assimilate the pollutants to attain the standard water quality standards. In case of agriculture, this component of water footprint would take into account the pollution caused by leaching of agrochemical residues and nutrients from the soil into the groundwater or surface waters.

The grey water footprint forms just over 11.3 % of the total water footprint of agriculture crop production [11]. However, when compared to the total grey water footprint of a region, the contribution from agricultural production stands out as the main constituent. In regions where agriculture forms the main livelihood providing sector, like South Asia, where more than 55% of the total population is dependent on an agricultural activity for their livelihood, the percentage is even higher than the global average. In Pakistan, agriculture contributes to 78.5 % of the total grey water footprint, while as in Bangladesh, China and India, the number stands at 70%, 62% and 55.5 % respectively. These four countries are among the top rice producing countries of the world, contributing at least 60% of world's rice production and accounting for more than 40% of the world's population. The average contribution of agriculture to the total grey water footprint for this 'rice bowl of the world' stands at 61%. This is higher than the world average; agriculture contributes more than 56% (this being the contribution of rice, maize, and wheat alone) of the total grey water footprint on a world level [11](Figure 4).

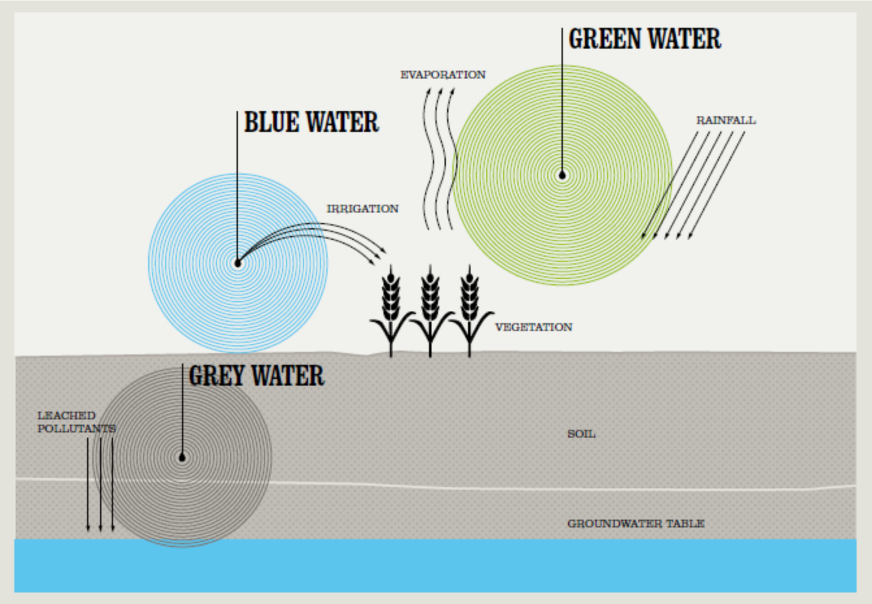



*Figure 4. Components of agricultural water footprint (Modified, original from SAB Miller and WWF, 2009)*

Agriculture, including croplands (12%) and pastures (26%), takes up almost 38% of the planet's ice-free land surface, accounts for 70% of the freshwater used in the world, and produces about 30% of global greenhouse gas emissions [12]. The current food production system increases humanity's dependency on fossil fuels and contributes to climate change. Meanwhile, climate shocks and extreme weather events can cause food price volatility that affects both consumers and producers around the world – hitting hardest in poor countries. The agricultural system has also doubled the flows of nitrogen and phosphorus around the world predominantly through the use of chemical fertilisers, causing severe water quality problems in rivers, lakes, and the ocean. It is also the single biggest driver of biodiversity loss. A growing number of international studies and assessments stress that more attention, public funds, and policy measures should be devoted to the agroecological approach in order to avoid these negative environmental impacts.

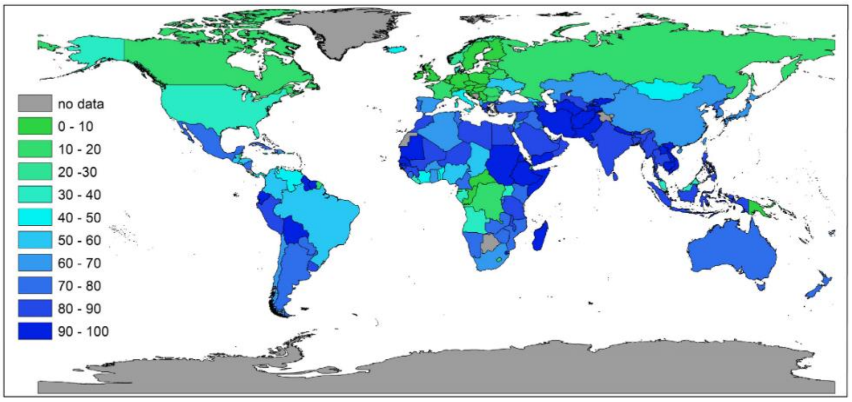



*Figure 5. Country wise freshwater withdrawals in agriculture as a percentage of total water withdrawals (Mancosu et al., 2015)*

The exclusive relationship between water and agriculture can be deduced from the fact that water use in agriculture accounts for more than 70% of the total freshwater withdrawals worldwide. And in some regions it goes up to 90% as well (Figure 5)[11]. Cotton and rice cultivation are the most water-intensive agricultural activities, and are the most important clothing fibre and staple food respectively. To produce one t-shirt worth of cotton on the farm, at least 12,000 litres of water are used in cotton cultivation. Similarly, to produce 1 kg of rice, 3000-5000 litres of water are used. This has led to the classification of rice as the most thirsty food crop [13].

The food production is vital for human sustenance and the demand for food is ever increasing with the increase in the world population. More than 98 % of the food worldwide comes from soil-based agricultural systems. However, in order to meet the demand, in order to ensure the right amount of supply to meet the food demand, there is more to it than just increasing the yield of the agricultural systems. Any technological intervention that is focussed on just one aspect of the agricultural system complicates the problem by ignoring other related factors. The introduction of high yielding varieties may have reduced hunger in the earlier decades in the poorer parts of the world, for example but the ecological costs have been high. These are the perils of using a natural production system similarly as an industrial production system, where a mere improvement in the production line or the raw materials makes sure you get an improved product. However, the agricultural system is not an independent production system. In addition to having interactions with its own immediate ecology, it has relationships with other systems on which the growth of food is dependent. Hence, whenever changes are made to the agricultural system, in any form – species grown, on-farm biodiversity, type of external inputs, soil management practices – it has a direct effect on the related systems.

## 1.3. Agriculture Interrelated Systems

It would be pertinent here to introduce the concept of Agriculture Interrelated Systems (AIS). The systems in agricultural ecosystem that are vital to the study of agricultural ecology. These environmental systems are related to the agricultural system in that they are influenced by agricultural practices and in turn influence future agricultural systems. That is, Agriculture Interrelated Systems (AIS) are those systems that have a reciprocal relationship with the agricultural system in general or the food production system in particular.

The hydrological system is an important component of the AIS, which forms the core of one of the burning issues in our world today. Agriculture is the largest consumer of freshwater worldwide and the food production forms a major part of the same [11,12]. Even the food production systems that are not soil-based, like aquaponics or hydroponics, are dependent on water, or one could rather say, they exist because of water. Based on the amount of water used and the way in which they utilize water, food crop systems can be divided into three: rain-fed systems, manual watering systems, and irrigated systems. Of these, the irrigated systems have the biggest share of the total water consumption in food production system. Agricultural crop production also has a high grey water footprint, which often forms the major portion of the total grey water footprint of a region [11].

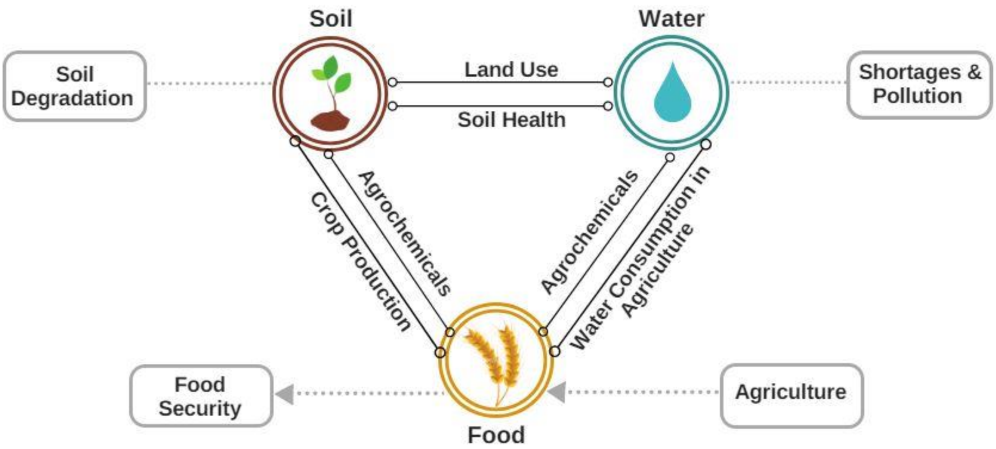



*Figure 6. The Water-Soil-Food nexus relationship (CC BY 4.0 Sumbal Tasawwar, Tavseef Mairaj Shah)*

Yet water is not the only natural resource that is vital to food production. Food production involves the interplay of more than just one environmental system. The natural resource of soil is vital for growing food. At the moment, more than 98% of the food consumed worldwide is grown from soil. However the condition of soils worldwide is far from ideal and the world is witnessing what scientists have called a soil health emergency and the fact that soil is considered the basic infrastructure for climate change makes matters more serious [14,15]. While as on one hand, soil is essential in the process of growing food, the different farming practices in vogue have a defining effect on the condition of soil. In this regard, it is important to adapt the way we grow our food in view of the current realities of the soil as well as the water resource system. The relationship and interdependencies of soil, water, and food can be visualised in the form of a triangular connection as shown in Figure 6.

The meteorological system is another system that can be included in the bracket of Agriculture Interrelated Systems (AIS). Weather conditions play a vital role in the proper seasonal functioning of the food growth cycle. The climate of a place dictates which crops can be grown in a particular region and hence the local farming traditions have accordingly been shaped.

However, in recent times, the increasing frequency of extreme weather events has led to losses in the agricultural productivity in different regions of the world, which in the worst case can also lead to a complete crop failure. However, agricultural practices also contribute to the dynamics of the local climates through being a major consumer of the water resource, hence playing a part in the hydrological cycle and also through the contribution of greenhouse emissions.

## 1.4. Problem statement

The challenges faced by the human community are multifaceted yet interconnected. The problems associated with changes in the global weather patterns, increase in the frequency of extreme weather events, broadly classified under the rubric of climate change, act to the disadvantage of human planning, agriculture, and general life in the urban as well as rural areas. However, these challenges are the only ones that we are facing in current times. These are challenges that are coupled and connected with other serious challenges faced by humanity, namely water scarcity and contamination, soil degradation and land-use change, food waste and nutrition imbalance, in addition to the now seemingly ever-existing energy crisis [16]. Increased migration, or at least the impression that of, across continents in recent years and the reactionary xenophobic, anti-Semitic, and Islamophobic movements gaining more traction with each passing day makes it more difficult for the governments to explore possible solutions. Hence negotiations and decision-making at the highest level often have to resort to compromises in order to have a consensus. In certain cases this also leads to a complete withdrawal of certain parties from the agreements. The withdrawal of the USA from the Paris Climate Agreement is a case in point.

In view of recent developments, taking stock of the underlying challenges in the food systems brought to light by the COVID-19 crisis, the International Panel of Experts on Sustainable Food Systems has called for an urgent paradigm from industrial agriculture to diversified agroecology-based agriculture [17]. In this regard, the solution to the wide-spectrum of challenges starts by correctly identifying the nature of the problem. Dealing with the individual challenges independent of each other has proven to be a non-starter in the long run. The one dimensional approach of dealing with a problem independent of its relationships and interdependencies with other challenges, in fact, has the potential of exacerbating the problem. The 'Green Revolution' and earlier climate agreements are a case in point. The earlier climate agreements failed to take on board a wide spectrum of stakeholders, excluding in the process that section of the society that face not just small losses but an existential crisis in the face of climate change—farmers.

As a result the need to improve our agricultural systems and the contribution that agriculture can make to climate change mitigation was ignored.

The Green Revolution was a reaction to plummeting yields and the resulting hunger mainly in South Asia. Under the aegis of Green Revolution, the use of agrochemicals like fertilizers and herbicides as well the development of irrigation canal networks in South Asia increased. This movement had it focus solely set on one dimension, possibly the only one visible at that time, of the agricultural systems—crop yield. It did help alleviate the condition of farmers as it resulted in an increase in the production of agricultural produce, dependent on market-dependent agricultural inputs [18]. This, however, came at a cost that is still being paid, decades down the line. The costs were associated with the negative effects of industrial agriculture on the soil ecology and the environment in general [19]. This line of thinking was a temporary solution to a long term problem as put by the initiator of Green Revolution himself, Norman Borlaug, who remarked that it was just a means for humanity to “buy(ing) time to adopt to more responsible policies to manage population growth and natural resources” [20].

However, the persistence with and rather the intensification of the measures suggested by green revolution has put the agro-ecological system at an existential risk, alarming even the proponents of industrial agriculture, prompting them to “add the ecological dimension” to crop improvement [21]. The effects have had manifold manifestation. The disappearance of local indigenous varieties of different crops that were best suited to local ecosystems in the name of productivity, that is being propped by increasing use of pesticides has disempowered local farmers and made them even more dependable on external inputs. The current level of disempowerment of farmers is evident from the fact that in India, every 33 minutes, a farmer commits suicide due to the inability to pay back loans as a result of crop failure, with some suicides having been effected by the consumption of pesticides [22,23]. Agriculture has fast transformed into a non-remunerative activity leading to a large flight to the urban areas for secure livelihoods and remunerative jobs, ultimately leading to unplanned and unsustainable urbanisation [24,25].

In order to have a realistic chance of the remediation of the current climate situation, measures that are net consumers of carbon are needed, in the context where a mere reduction or a standstill of emission levels does not alone suffice. Rice is a staple for more than half of the world population and it is one of the resource intensive crops. Water use in rice is the highest among field crops; the amount of mineral fertilizers and pesticides used in rice cultivation is unparalleled owing to the large scale at which rice cultivation is done, concentrated mainly in those regions of the world that are deemed to be the most vulnerable to the negatives of climate change, manifest majorly in the form of increased frequency of extreme weather events. Given that more than half of the agrochemical input in agriculture remains unutilized by the crops or the soil, the major portion of the agrochemicals end up as contaminants in the groundwater and also leach away vital trace elements from the soil, hence leading to a decrease in the soil quality and by extension, food quality. This has also led to the unavailability of groundwater resources to the farmers with an increasing tendency, in many parts of the Indus-Ganga plain, a region that falls under the classification of regions most vulnerable to climate change.

Rice farming also contributes a major portion of the $CO_2$ eq. greenhouse gas emissions from the agriculture sector. Agriculture contributes 7 % of the total anthropogenic $CO_2$ eq. of GHGs worldwide, and the percentage is higher in USA and EU 28 countries, at 9% and 10 %, respectively, with a highest of 31% in Ireland. Irrigated flooded rice farming which is the most common way of growing rice worldwide contributes greenhouse gas emissions via two pathways: methane gas production from the anaerobic digestion of organic matter and the nitrous oxide generated from synthetic nitrogen additions to the soil. Methane emissions from rice cultivation globally account for one-half of all crop-related greenhouse gas emissions and this accounts for 2.5% of the current anthropogenic warming.

On an average, 2,500 litres of water need to be supplied by rainfall or by irrigation to a rice field to produce 1 kilogram of rice. The variability is large ranging from 800 litres to 5,000 litres, depending on factors like the variety, fertilization regimen, and disease control strategies used. On an average, it takes around 1,500 litres of evapotranspired water to produce 1 kilogram of rice. So, almost half of the water supplied to rice fields practically ends up as water vapour. Around one-quarter to one-third of the world's 'developed freshwater resources' are used to irrigate rice (the staple food for almost half the world population). In this respect, the current model of rice cultivation owing to its wide ranging relevance has been to critically viewed in the context of the water crises worldwide, the changes in weather patterns and the increased frequency of extreme weather events, and the deteriorating effects of land use change of the soil health. There is a growing need to restructure agricultural activity in the light of these new realities. Innovative irrigation techniques like alternate wetting and drying (AWD) provide a good chance in this regard to reduce the water consumption in agriculture. Mulching improves the water retention capacity of the soils, seen particularly for rice cultivation. Intercropping another food crop together with rice can be a good way to achieve this; the residue being mulched into the soil eventually.

This research is about the relationship between agricultural systems and the ecology, examining how can changes made in the agricultural system at the farmer's level have the potential of having wide ranging effects on the ecology and environment. In the first part of the work, the different aspects of this issue are analysed in an extensive review, followed by the detailing of the experimental work done at laboratory and field levels. In this regard, the relevance of agroecological strategies in rice cultivation like the system of rice intensification (SRI) and intercropping is studied. SRI is a package of individual practices aimed at increasing the productivity of rice farming but not at the cost of resources or the climate. SRI and allied practices have the potential to contribute towards a water-conservative and climate-friendly food production system. The experimental studies also explore the potential of intercropping nitrogen-fixing plants with rice under SRI as a further innovation in the rice farming system. The incidence of weeds under dry soil conditions under SRI has often been cited as a criticism of SRI and weeds are one of the single largest limiting factors in rice farming in South Asia, representing 6.6% of the total yield gap [26]. Intercropping is expected to have a restraining effect on the weeds that grow in absence of water, under SRI and forms one of the main cited limitations of SRI [27,28]. This work deals with the systems approach of tackling the challenges of water scarcity, food security, and soil degradation under the overarching conditions of a rapidly changing climate—socioeconomic, political, and ecological.

# 2. REVIEW OF RESEARCH ISSUES

## 2.1. Water and agriculture: an overview

Crop production is the major consumer of freshwater worldwide. In this view, in framing any policy on water protection and water treatment or proposing solutions to the water crisis, water-use in agriculture needs to be given due consideration. Under the current agriculture model, water consumption in crop production does not only include water that is directly used in irrigation but also the indirect consumption of water resulting from the contamination of groundwater and surface water associated with the use of synthetic fertilizers and other agrochemicals. The challenges of food security and water scarcity are hence to be seen as part of a nexus relationship rather than being isolated, stand-alone challenges. As is the case globally, improving water use efficiency in irrigated agriculture is vital for meeting future food requirements in South Asia. India is the largest user of groundwater globally and being the second most populous country in the world, the importance of water use efficiency cannot be understated.

It is worthy to note here that empirical evidence on water use for domestic and agricultural purposes in the US points out that the adoption of water efficient technologies does not necessarily reduce the total use of water; in some cases it even leads to an increase in the same [29,30]. Fishman et al. (2015) reported a similar aspect of water use by focussing on water use decisions taken by farmers in developing countries. In developing countries where water withdrawal is often unregulated, irrigated agriculture is placing increasing pressures on the freshwater resources, which have decreased over the past decades not just in per capita terms but also in absolute terms. Increasing water use efficiency is hence required to transform agriculture into a sustainable mode of growing food and securing livelihoods for millions of smallholder farmers worldwide. These interventions need to go beyond just introducing new technologies like drip and sprinkler irrigation techniques, the implementation of which does not necessarily translate to reductions in groundwater extraction despite having the potential to do so. This is because the impacts of such technologies are heavily dependent on farmers' decisions; half of the reductions are lost due to the expansion of irrigated area. Hence, in addition to technological interventions the farmers need to be sensitised towards the problem [31]. Participative incentivisation of water conservation strategies in agriculture could be one way to deal with this challenge. In absence of such incentivisation or sensitisation, expectations of the water saving capacity of the new technologies are inflated at times [31]. One of the challenges related to farmer behaviour Fishman et al. (2015) pointed is the 'realistic scenario' in which farmers expand the irrigated area with the newly introduced techniques until the baseline (pre-adoption) water use levels are reached. In this case, despite the adoption of water saving irrigation technologies, the total water use remains the same. In this case, the total water extracted will still remain the same, although you may have extra production, hence the problem is still there.

In regions such as the Western Gangetic basin, which contribute the major share of food grains in India, the maximal theoretical efficiency can reduce the rate of water table decline but cannot reverse it. For that to be achieved, sustainable water management strategies need to be introduced that shift the water requirements of growing food to the lower side. Hence a water policy based entirely on the promotion of water saving technologies is inadequate in absence of incentivisation of water conservation strategies or strategies that reduce the need to expand irrigated area [31]. This could be achieved by increasing the yield per drop with farming systems like SCI/SRI (System of Crop Intensification/System of Rice Intensification).

Current realities like changing weather patterns, increasing frequency of extreme weather events, and other associated effects grouped under climate change coupled with the increasing population have intensified the need as well as the search for measures to conserve water through the application of water conserving techniques in agriculture (Easterling, 2007). However, Ward et al. (2008) report that water conservation subsidies are unlikely to reduce water use under existing conditions. They argue that for real water savings, institutional, technical, and accounting measures are needed "that accurately track and reward reduced water depletions" (Ward et al. 2008). With many countries already reporting water scarcity and hence the inability to meet their agricultural, environmental, and urban needs, worldwide water demand continues to grow [34,35]. This demand includes growing enough food for the current population and the 2 billion more that are expected to increase in the next 50 years, with analyses estimating that 60% of this added food will come from irrigated agriculture [36,37]. This needs improved and sustainable crop water use efficiency [38–44].

An improved performance of crops with more crop per drop will result in more water available for other uses. A case in point being that more than a billion people worldwide lack safe affordable drinking water. Hence there is a direct link between increasing irrigation efficiency and water availability and water supply [43–45]. More crop per drop here is sustained water supply elsewhere. In this regard, water applied in irrigation can broadly be divided into two parts, based on where it eventually ends up. One portion of the irrigation water ends up in evapotranspiration while as the other portion returns to the basin as return flow. The water lost due to evapotranspiration is associated with plant water use, while as the return flow is used at other times in other locations. In this regard, if the return flow is loaded with excess agrochemicals, it reduces the usability of the water and also reduces groundwater quality. In this case, similar to cases when return flows travel to a saline body or brackish groundwater, most applied water is consumptively used because the unused irrigation water is lost for future freshwater use. Ward et al. (2008) hence suggest a re-examining of the widely held belief that interventions focussed solely on increasing irrigation efficiency will relieve world's water crisis. This has to be accompanied by a sensitisation of the farmers towards more crop per drop strategies. In this regard, technologies like drip irrigation are deemed to be important because of greater water productivity and food security but it may not necessarily reduce water use when considered from a basin scale [43,46,47]. In addition to measures such as accounting and measuring water use, Ward et al. (2008) suggest strategies that reduce non-beneficial evaporation from soil and switching to lower water consuming crops [48,49]. This could also be achieved by using agroecological systems like the System of Rice Intensification, which combine the aspects of reducing evaporation from soil and lowering water needs of crops.

Human water use has more than doubled over the past 50 years and also affected stream flow in various regions of the world. The impact of human water consumption on the intensity and frequency of hydrological drought over the period of 50 years between 1960 and 2010 is marked. Human water consumption intensified the magnitude of drought by 10%-500% in different regions of the world. On the other hand the frequency of drought conditions increased by 35% in Asia, which represents the worst case. While as in Asia, the water consumption in irrigation is majorly responsible for intensification of hydrological droughts, in the developed regions, it is mainly industrial and household consumption. Human water consumption is projected to remain a major factor intensifying hydrological drought in the next decades [50]. Hence a rethink of the way irrigation of agricultural fields is achieved seems to be a vital part of the overall water use strategy.

The extent to which human water consumption affects water availability and drought can be elucidated by first differentiating between meteorological drought and hydrological drought [51]. Meteorological drought is the situation caused by the lack of enough precipitation, which ultimately results in hydrological drought as it begins to affect larger areas. This leads to negative effects on water supply and food production [52–54]. Although recent studies have pointed towards the intensification of meteorological drought conditions owing to anthropogenic global warming [55–57] due to increased evaporative demand and altered monsoon circulation in Asia and Africa, the intensified hydrological conditions over the past decades have also been influenced by increased human water consumption that has more than doubled in the same time [54]. Water use in irrigation forms a major part of this increased human water consumption, which has also exacerbated the incidence of hydrological drought [53,54]. The intensification of hydrological droughts, i.e. drought intensity and frequency, due to human water consumption can occur even in water-rich regions or areas with no increased local water consumption as a result of upstream human water consumption. This can also lead to water-based conflicts between riparian states e.g. the Kashmir-Pakistan-India tripartite conflict.

While as in major developed countries, drought intensification is driven by water consumption at industrial and household level, in developing regions like Central Asia and South Asia, where irrigation water consumption amounts to more than 90% of total water consumption, the intensification of droughts is more severe [58]. This again points to the importance of introducing sustainable interventions in how irrigation is imagined in countries most vulnerable in the changing global scenarios. This also hints at the disadvantage the food producing countries are at and evidences the unfair socio-economic water use balance between the Global North and the Global South. This effect is more pronounced in India and Pakistan, as it is in these countries that the severe drought conditions are driven by human water consumption (90% in agriculture). This increased pressure on water resources can also aggravate groundwater overdraft, which has resulted in groundwater depletion over large areas (the so-called *food basket* areas) in Iran, Pakistan, India, China, Mexico, and USA [59]. In a business as usual scenario, the hydrological drought conditions are expected to become more severe given the increasing demand for food, potentially having disconcerting impacts on the societal relations and ecosystem services [53,60]. Different studies have pointed to the high potential of good water and land management practices to increase the water use efficiency in agriculture and hence facilitate adaptive response to aggravating drought conditions, particularly in Asian countries [50,61,62].

Jägermeyr (2016) studied the global potential of improved on-farm water management practices in closing the food gap while at the same time reducing water scarcity. The potential that on-farm irrigation efficiency improvements have in this regard is evident from the numbers: irrigation efficiency improvements can save up-to 48% of non-productive water consumption in many river basins worldwide; these savings, when rerouted to water-deficient food growing systems, can increase the global calories production by 26%. In view of an unabated climate change scenario, improvements in water management have the potential to buffer its effects on crop yields, by increasing global production by up-to 40% and closing the water-related yield gap by up-to 60% [63]. This is significant given that the current food growing systems are already challenging planetary boundaries and the need for extra calories production is expected to continue to increase in the coming decades [64–68]. Given that the current negative externalities of the food system ruling out an intensification of agriculture from a conventional perspective, increasing production on existing agricultural land by managing available resources more efficiently, placing less pressure on the environment and sustaining future capacities, i.e. sustainable intensification, can thus an important part of a solution and high on the global policy agenda.

In this regard studies have classified the role of water harvesting (WH) and soil moisture conservation (SMC) techniques as significant in increasing smallholder yields while at the same time improving resilience in changing climate scenarios [69–72]. Although such techniques are already in practice in different parts of the world in different forms, there is still an enormous potential to scale them up [63]. Some of the SMC techniques to reduce non-productive moisture loss include organic mulching or cover crops, and different conservation tillage systems. In addition to increasing water use efficiency, these techniques also provide some additional benefits for the crops, which include avoiding water stress, suppressing weed growth, and improving cold tolerance [73]. For example, organic crop residues covering 50% of the soil surface have been observed to reduce soil evaporation by around 25% [63]. It is to be noted here that water management is not a complete solution, a panacea, when applied in isolation. It needs to be applied together with soil and nutrient management strategies to harness the strong synergies between the water, soil, and nutrient systems [72]. A case in point being cropping systems that are highly nutrient-deficient as of now, in which case the best practice water management strategies cannot function to the benefit of the farmers and might even lead to cases of false negative results [69,74].

South Asia being the world’s largest food growing, food producing region, the sustainability of its agricultural system attains global significance. The dependence of the region’s agricultural production on its groundwater resource cannot be overstated. A case in point is agriculture in India, where groundwater irrigation currently boosts crop production by 170 million people worth of food needs. However the groundwater situation in the Indus-Ganga basin looks grim at the moment, with overexploitation having led to drastic declines in the groundwater levels. For example, in north-western India, groundwater levels have dropped from 8 meter below ground level to 16 meter below ground level in the last three decades. Between 2002 and 2008 alone, 109 km3 of groundwater was lost in north-western India, which includes the agrarian state of Punjab. In comparison with the Central Valley region of California, US, the loss of groundwater in Punjab is an order of magnitude higher. This points to the criticality of interventions in this field in the region. This puts India's smallholders—the backbone of India's food security—at the forefront of the fight against water scarcity and water misuse [75]. In addition to food security, agriculture in India contributes significantly to the social and political economy, accounting for 20 % of India's GDP and being the largest employer in India; India exports $39 billion worth of raw agricultural products and 4.4 million tons of milled rice annually. There is a need to foster a multidisciplinary approach to counter the intertwined challenges of water depletion and food insecurity in the whole South Asian region, which is home to one-third of the world population and also to almost half of the world's extreme poor, that primarily rely of on agriculture to secure their livelihoods [75]

One such approach could be the use of numerous indicators that have been theorised to quantify the use of water resources for different human uses. On of such indicators is the blue water sustainability index (BlWSI), which incorporates the two main aspects of water use viz. non-renewable groundwater use and non-sustainable water use, which are usually ignored in water use calculations. BlWSI is special in that it pays special attention to the use of non-renewable groundwater resources, which are the major source of food production in many regions of the world. Using BlWSI as the reference, Wada et al. (2014) reported that the global non-sustainable water consumption is showing an increasing trend, especially since the 1990s and that this trend is projected to continue towards the end of this century[76]. From Figure 7 [76], it can be seen that the most intense water consumption is occurring in the regions where the major part of the global irrigated lands lie. By the end of this century, the trend is expected to continue, with South Asia being among the regions with the most intense increase. On paper, non-sustainable water use may be a regional problem, but it has socioeconomic and socio-political consequences on a global level. International water sharing treaties, international food trade, international migration are some of the aspects that scale the problem up from regional to global level. Innovations in water management, crop management dietary diversification, and incentivisation of efficient irrigation have been proposed as measures to counter the critical scenarios in future [61,76–78].

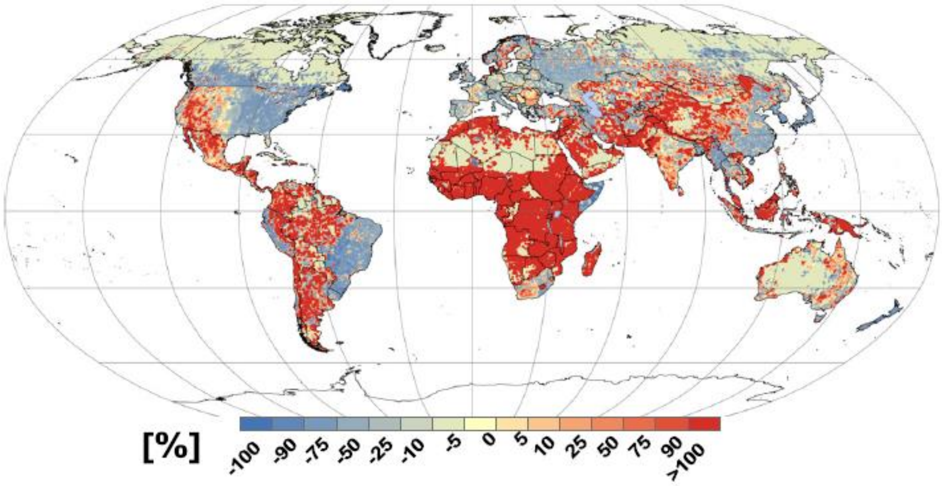



*Figure 7. Global map of the projected change (%) in total blue water consumption from 2010 to 2099 (Wada et al., 2014)*

On a broader level, recent events have reaffirmed the need to revisit the general approach of food 'production'. Food production under the current rural-urban binary system is almost exclusively restricted to areas designated as 'rural' while as the 'urban' is imagined as the centre of industrial production or/and industrial dynamics, and as a place that serves as the hub of consumption of all products. In this scenario, the urban is vitally dependent on the supplies from the rural, especially when it comes to food. A mere mention of a possible shutdown sends people into a frenzy of hoarding of different food items, either because of the belief that supplies won't last and that the supply lines may get disturbed. The current Coronavirus COVID-19 crisis is a case in point. Drawing on the examples of two cities from the ancient and medieval era, from Classic Maya civilization and Byzantine Constantinople, respectively, Barthel et al (2012) conclude that urban farming has been a vital feature of urban support systems and that agricultural production is not "the antithesis of the city" but an acitivity that contributes to the resilience of cities [79]. A similar pattern is seen in the establishment of the first capital of the Islamic civilisation—the city of Medina [80]. The oldest available plan of this city shows a populated core of the city surrounded by gardens that would provide the city with food supplies (Figure 8). The concept of garden cities is pertinent to mention here that envisages locally produced food in a cooperative setup. In this regard the new town concept (*Das Neue Dorf*) can also provide the guiding principles [81].

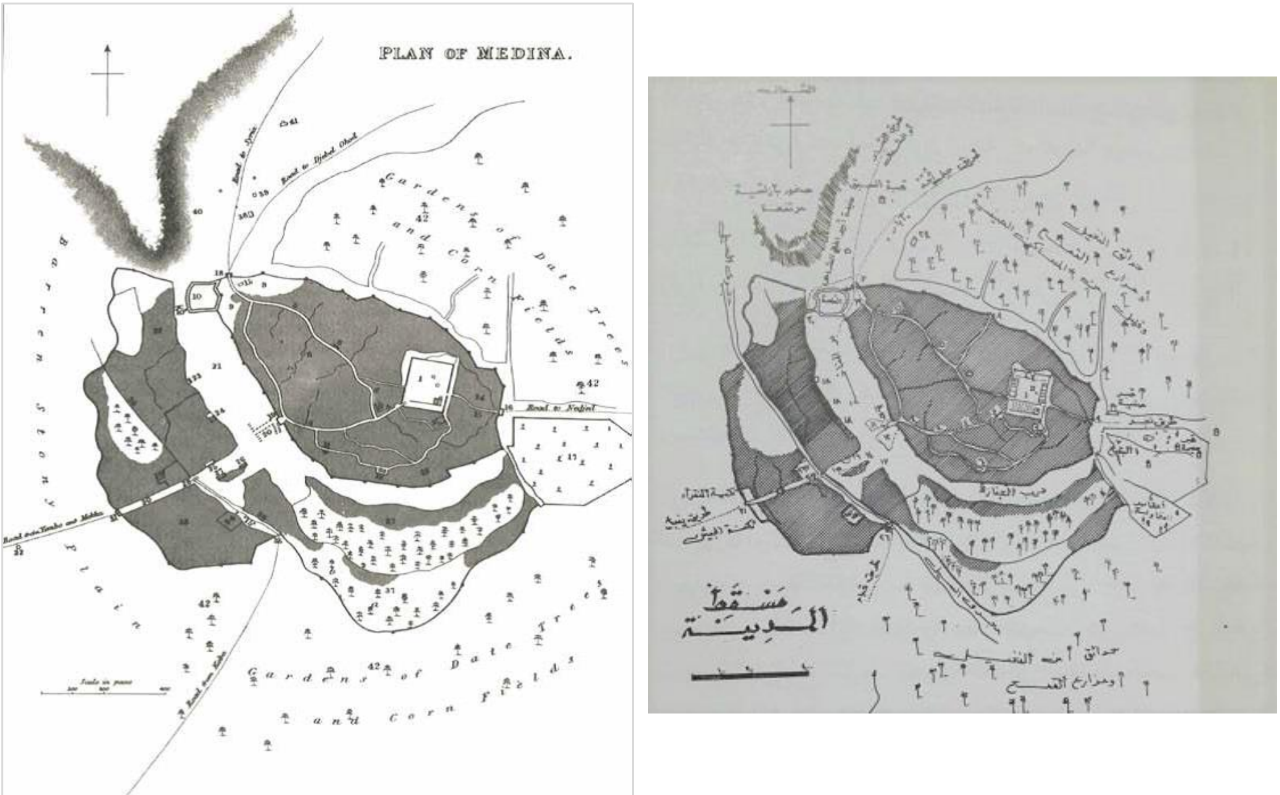
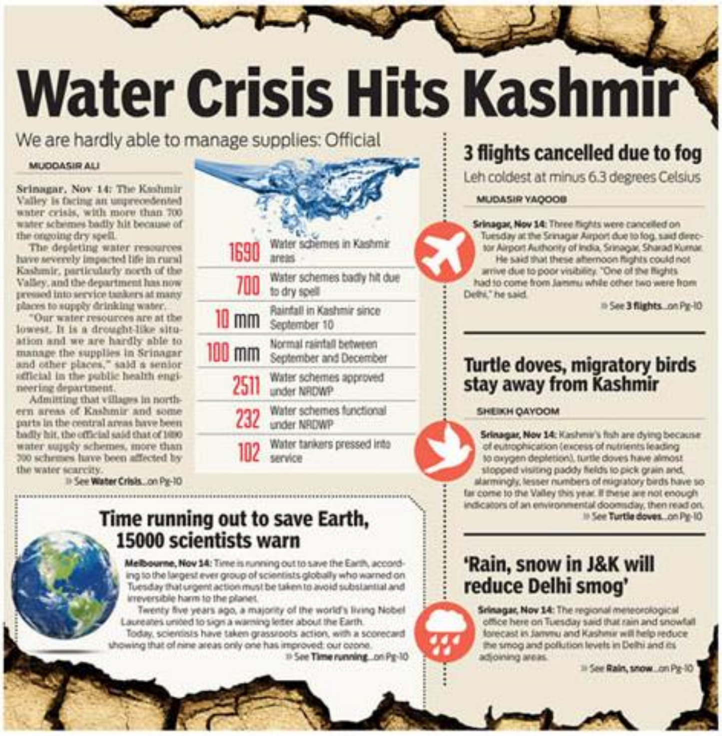



*Figure 8. The populated centre of the city of Madina (in dark colour) surrounded by food gardens on three sides (Burton, 1914)*

The last two hundred years have seen the enormous development of cities as the centre of human activity, with the current percentage of the total world population living in cities at more than 50%, which is expected to rise to 75% in the coming decades, under a business as usual scenario [82,83]. Continuous technological progress has led to multiple waves of space-time compression feeding off the surplus energy of diminished returns subsidized by fossil fuels [84,85]. In such a scenario, large cities feed themselves by the globalized food system, completely dependent on fossil fuels, sequestering food from different regions of the world [86–89]. While the space-time compression has decreased the importance of geographical barriers and hence increased the resilience of cities in no-crisis and medium-crisis situations, the supply lines still remain dependent on transportation over short and long distances, which are hence vulnerable to a collapse under a severe crisis, in which international or even interstate borders might need to be closed [79,90,91]. As an example, Lindgren and Fischer (2011) have reported that, in case of a collapse of the fossil-fuel dependent food system, the city of Stockholm might be less than two weeks away from starvation after household and store supplies are exhausted [92]. While as in the World Wars I and II, urban gardens were vital in providing food—allotment gardens had provided 2,000,000 tons of vegetables in Britain by 1918—a similar blue-green infrastructure in contemporary cities is rapidly vanishing, if at all present [79,93,94]. In this case the ancient and medieval urban systems provide us examples of cities that did not depend on fossil fuels [79] mainly because they had their own share of food growing systems. Given that agricultural activity in urban settings has the potential to significantly support the resilience of modern cities, farming techniques that are less resource intensive can be implemented without the need for extensive infrastructure build up. The potential of cities to be self-reliant in terms of food is however not impossible in the current times. The example of Havana, Cuba is a case in point. The US blockade in the early 1990s caused a shock in the food, fertilizer, and oil supply lines in Cuba, hitting the urban centre of Havana in particular. However, 10 years later, Havana was home to 400 horticulture collectives with an annual production of 8,500 tons of vegetables, 7.5 million eggs, and 3,650 tons of meat using agroecological methods [95], improving the socioeconomic conditions of the people and making the city resilient to any future trade breakdown [79].

Water contamination makes it inaccessible and unusable in many regions of the world, northern Indus-Ganga plain, in the Punjab region. Groundwater contamination in the Bengal and Bangladesh regions. Water powers the world food systems. Rice is the world’s most thirsty food crop, with anything between 3000-5000 litres of water. Rice is single most important staple food worldwide, with more than 50 % of the world population having rice as in least one of their staple diets. In South- and South-East Asia, rice cultivation is not just the source of food and hence a cultural good, rather it is the source of livelihoods for a major part of the population, hence is important to the social balance of the region.

However, water scarcity and water contamination in the region and elsewhere is affecting and in some cases stopping rice cultivation. In the Kashmir region, for example, in the year 2018, the local irrigation department advised the local farmers not to cultivate rice owing to the low precipitation and hence low water levels in the rivers feeding the rice irrigation system (Figure 9). This also points to the complexity introduced by the change in weather patterns, the increase in the frequency of extreme weather events, or changes in the average temperatures, also sometimes clubbed under the blanket term of climate change on the food production systems. Water is vital to human life and security in more than one ways, but in all ways connected to food production.



# Water Crisis Hits Kashmir

We are hardly able to manage supplies: Official

MUDDASIR ALI

**Srinagar, Nov 14:** The Kashmir Valley is facing an unprecedented water crisis, with more than 700 water schemes badly hit because of the ongoing dry spell.

The depleting water resources have severely impacted life in rural Kashmir, particularly north of the Valley, and the department has now pressed into service tankers at many places to supply drinking water.

"Our water resources are at the lowest. It is a drought-like situation and we are hardly able to manage the supplies in Srinagar and other places," said a senior official in the public health engineering department.

Admitting that villages in northern areas of Kashmir and some parts in the central areas have been badly hit, the official said that of 1690 water supply schemes, more than 700 schemes have been affected by the water scarcity.

» See **Water Crisis**...on Pg-10

| | |
|---|---|
| 1690 | Water schemes in Kashmir areas |
| 700 | Water schemes badly hit due to dry spell |
| 10 mm | Rainfall in Kashmir since September 10 |
| 100 mm | Normal rainfall between September and December |
| 2511 | Water schemes approved under NRDWP |
| 232 | Water schemes functional under NRDWP |
| 102 | Water tankers pressed into service |

## Time running out to save Earth, 15000 scientists warn

**Melbourne, Nov 14:** Time is running out to save the Earth, according to the largest ever group of scientists globally who warned on Tuesday that urgent action must be taken to avoid substantial and irreversible harm to the planet.

Twenty five years ago, a majority of the world's living Nobel Laureates united to sign a warning letter about the Earth.

Today, scientists have taken grassroots action, with a scorecard showing that of nine areas only one has improved: our ozone.

» See **Time running**...on Pg-10

## 3 flights cancelled due to fog

Leh coldest at minus 6.3 degrees Celsius

MUDASIR YAQOOB

**Srinagar, Nov 14:** Three flights were cancelled on Tuesday at the Srinagar Airport due to fog, said director Airport Authority of India, Srinagar, Sharad Kumar.

He said that these afternoon flights could not arrive due to poor visibility. "One of the flights had to come from Jammu while other two were from Delhi," he said.

» See **3 flights**...on Pg-10

## Turtle doves, migratory birds stay away from Kashmir

SHEIKH QAYOOM

**Srinagar, Nov 14:** Kashmir's fish are dying because of eutrophication (excess of nutrients leading to oxygen depletion), turtle doves have almost stopped visiting paddy fields to pick grain and, alarmingly, lesser numbers of migratory birds have so far come to the Valley this year. If these are not enough indicators of an environmental doomsday, then read on.

» See **Turtle doves**...on Pg-10

## 'Rain, snow in J&K will reduce Delhi smog'

**Srinagar, Nov 14:** The regional meteorological office here on Tuesday said that rain and snowfall forecast in Jammu and Kashmir will help reduce the smog and pollution levels in Delhi and its adjoining areas.

» See **Rain, snow**...on Pg-10

*Figure 9. Newspaper cutting from 2018 about the looking water scarcity (Greater Kashmir)*

## 2.2. Soil health worldwide: Global Soil Status

### 2.2.1. Soil health and food security

The IPBES report released in September 2019 points to a soil emergency that we are experiencing. Although the status of the soil resource is different in different regions of the world, the common denominator in all the regions is the rampant soil degradation and reduction in soil quality to different degrees. The major anthropogenic, or rather the most controllable, cause behind soil degradation is the use agrochemicals and unsustainable agricultural practices [96]. A proper balance between the input and losses of nutrients and carbon essentially controls the stability of soil systems. Humans have been exploiting agriculture since a few thousand years now, with the expansion, both in terms of area and in terms of utilization, being proportional to the growth in the world population as well as diversifying needs. In the process, however, the world soil resources have been depleted and soil continues to be lost at rates that are many orders of magnitude higher than the rates at which soil can possibly be replenished. Agricultural practices also practically led to the ignition of Earth's carbon reservoir, which in combination with anthropogenic warming from other sectors can further lead to accumulation of greenhouse gases and hence exacerbate climate change. Land cultivation and clearing has, for example, contributed a major fraction of the total anthropogenic greenhouse gas emissions in the last two centuries [97]. Well into the 20$^{th}$ century, the combined emissions contribution of cultivation and biomass burning to atmospheric carbon dioxide exceeded that of fossil fuels [97]. The need to adapt agricultural practices in the light of such relationships becomes more current than ever [98].

However, as clear it may seem, the adaptation of agriculture in the age of climate change must not be seen as a reaction to climate change induced scenarios. It can rather be assumed that the climate emergency provided for a positive shock which led to the realisation that we are living in an age of soil emergency, which needs drastic measures in order to sustain the different allied ecosystem services including food security! The role of the biological and chemical processes in soil in the global carbon and climate calculations is becoming increasingly popular, as the report released by IPBES (2019) shows [99,100]. Only in a scenario where the contribution of soil processes to allied ecosystem services like water availability and water purification is clear to the stakeholders can proper policies around soil management be realistic [15]. Managing soil the right way can be vital part of the solution to adapt to and mitigate climate change in a timely fashion. On the contrary, the consequences of continued mismanagement of soil will be seen in the human society for centuries to come. Hence the management of soil, through agricultural practices, has bearing on the long term health of the human society.

Global soils however do have the capacity to approach the original carbon storage capacity and even regain a significant portion of the present fossil fuel emissions through changed soil management strategies in agriculture. This includes measures to increase the organic content of the soil, which as an agriculture practice has both ecological and agronomic benefits [101]. The effect of different management practices on the rate of soil carbon sequestration is well documented and can hence be used to design agro-ecological solutions for different farming systems in different agro-climatic zones [102]. In industrialised countries, food prices became lower and lower through the late 20$^{th}$ and early 21$^{st}$ centuries, mainly due to the introduction of energy intensive agriculture. Low-cost energy driven agricultural machinery forced a migration of rural hand-power towards the urban centres creating challenges of its own. Additionally, fossil fuel driven ‘cheap’ energy meant soil nutrients lost in soil due to intensive agriculture could be replaced, at least theoretically, by applying industrially manufactured fertilizers [103], including primarily nitrogen fertilizers manufactured by the Haber-Bosch process. This led to the paradigm shift known as the green revolution [104] with which the earlier paradigm of increasing cultivated area to increase yields was replaced by the notion of using fertilizers to increase yield with the same cultivated area [105]. This paradigm shift did increase the yield of food and reduced hunger, but it came at an ecological cost. For example, approximately 80 %

of the total nitrogen manufactured by the Haber-Bosch process is used to produce fertilizers for agriculture. However, only 17% of the total nitrogen applied is consumed by humans in the form of crop, dairy, and meat products [104,106].

The effects of the current mode of agricultural intensification on soil degradation are well documented, which include loss of organic matter, salinization, and acidification of the soils [107]. It is estimated that presently 33% of coils are moderately to highly degraded due to the aforementioned mechanisms [108] while as 52% of agricultural land is already affected by soil degradation, ranging from moderate to severe [109]. With a further expansion of cultivated land excluded from the list of possibilities and the ecological externalities of chemical-intensive agriculture increasingly coming to the fore, a better management of our existing soil resource seems to be the desirable and opportune alternative [98]. It is pertinent to mention the role of soil organic matter in this regard. Organic matter ensures the retention of plant available water in the soil known as 'Green Water', which is responsible for 90% of the global agricultural production [110]. Hence, it has been found that soul management practices that increase the organic content of the soil contribute to increasing performance of the crops through two mechanisms: by increasing the availability of water and by increasing the availability of nutrients [11,111]. The erosion of agricultural soil is one of the most destructive human perturbations in the ecosystem. The loss of soil, on the other hand, not only affects the food production through loss of nutrients but also the water quality and aquatic ecology by polluting the same [112]. In this regard, utilizing symbiotic relationships between different plant types to provide nutrients to the crop plants can be one sustainable alternative e.g. legumes fixing atmospheric nitrogen for crop plants, in an intercropping scenario. Similarly, naturally occurring salts can be used as the source of other nutrients required for plant growth. In this way, the energy intensive production of plant nutrients can slowly be phased out of agriculture, hence reducing the ecological footprint of our food growing system [98].

Another possibility to close the nutrient loop could be using nutrients from the 'waste' streams that are otherwise environmentally damaging and economically taxing to manage. Managing these 'waste' resources can be a vital contribution in the field of environmental sciences, reducing the demand for imported nutrients on one hand and increasing the efficiency of water treatment facilities on the other hand [113]. Any framework of soil management must focus on the adjusting the pace of utilization of the soil resource with the rate of replenishment of the same through regenerative measures. This should follow a three pronged approach: (i) balancing carbon inputs and losses, (ii) balancing soil erosion and production, through prevention and regeneration, and (iii) balancing nutrient cycles [98].

This is possible when soil management is viewed from a nexus perspective, which has so far been only talked of as the Water-Food-Energy nexus. The first State of the World's Soil Resources Report by the Intergovernmental Technical Panel on Soils has identified global soil erosion as the main threat, which not only leads to food insecurity in many regions of the developing world but also leads to deteriorating water quality in the developed regions and have suggested a reduction in the overall use of mineral fertilizers in agriculture worldwide [114]. In South Asia and Sub-Saharan Africa, organic carbon and nutrient imbalance, and salinization have been identified as the main threats to soil after erosion (Figure 10).

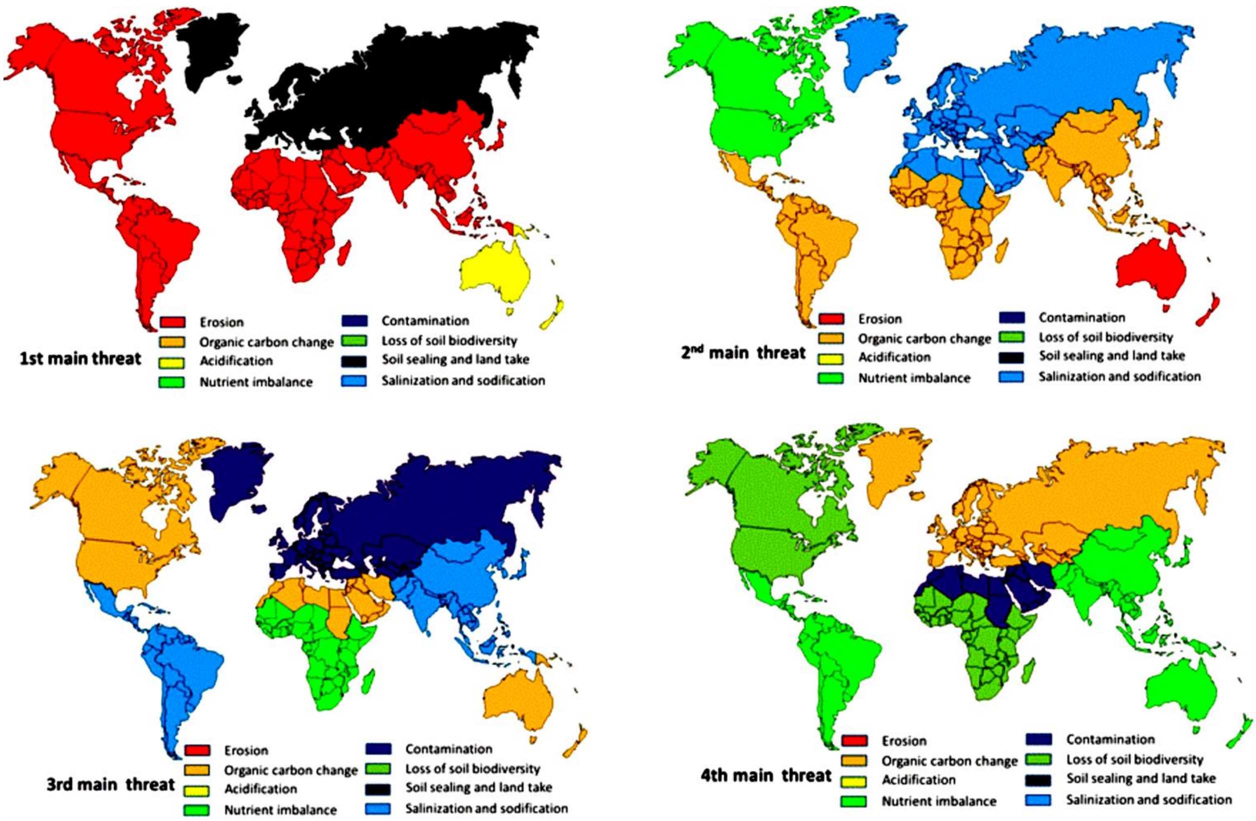



*Figure 10. Map based region-wise assessment of the four main threats to soil (Montanarella, 2016)*

The loss of soil organic carbon and nutrient imbalance are the most significant threats to soil, even at a global level. In view of the importance of soil in providing different ecosystem services, in addition to food supply, it is recommended to expand the scope of nexus studies to Water-Soil-Food-Energy nexus [107]. Lal (2010) has advocated that "while advancing the study of basic principles and processes, soil scientists must also reach out to other disciplines to address the global issues of the 21st century and beyond" [115]. Hence, when addressing the problem of worldwide food security, it is not just the food production that has to be kept in mind, but all other ecosystem services dependent on the well-being of soil. If only crop yield is the parameter on which the focus is laid, it can well affect the other soil ecosystem services, and that too in the long term. Thus any new agricultural strategy must duly take into consideration as to how the purported benefits of higher agricultural productivity weight against the loss of other ecosystem services provided by soil. Or, an even better way would be to mainstream agro-ecological practices that take care of both the production aspect of soil as well as the ecosystem services aspect.

As a prognosis to the status report of world's soil resources, Richter and Markewitz (2001) reported that the proper management of the soil resource is essential for the circulation of chemical elements, water, and energy for the human well-being; while as its poor management makes being optimistic about future a hard choice to make [98]. In this regard, Lal (2008) has recommended increased focus on the use of crop residues, compost, mulching, and additives that enhance microbial activity in the rhizosphere, in addition to the use of complex cropping systems like intercropping and multicropping [111]. The organic agriculture movement is a good example in this regard, which approaches the soil emergency from a systems point of view. From a soil health perspective, the focus of organic agriculture on using organic additives rather than industrial fertilizers and pesticides has shown different benefits, owing majorly to the increase in the organic matter content of soil. On the other hand, organic agriculture on average is 15% less energy intensive compared to conventional systems [41,116]. However, it has also been reported that organic agricultural systems often have lower yields and yield stability [41,116]. These are areas that can be worked on, also keeping in view the other ecosystem services organic agriculture might have a larger positive contribution to, in the wider framework of the Water-Soil-Food-Energy nexus. For example, organic agriculture has been reported to support biodiversity levels at least 30% higher than conventional agriculture [117]. A failure to realise the importance of our finite soil resource in sustaining the present and future generations can have serious consequences in the times to come [107].

### 2.2.2. Soil and UN Sustainable Development Goals


*Figure 11. The 17 Sustainable Development Goals mandated by United Nations (UN)*

Soil health and the proper management of the soil resource can play a decisive role in the achievement of different Sustainable Development Goals (SDGs) mandated by the United Nations (UN) (Figure 11). Soils play an anchor role in food systems; fixing food systems and achieving the UN SDGs have been termed as the two sides of the same coin [118]. Soil related measures have a central position when considering SDGs and the soil-water-plant-climate system and aiming at reaching several of them at the same time using a systems approach. And, in turn the SDGs provide soil science with goals of high societal relevance and recognition in the form of 'points at the horizon' in order to formulate their work in clear terms for all the stakeholders to understand [119]. This is also facilitated by the fact that 195 countries of the world have signed the SDG agreement and are legally obliged to issue progress reports of their efforts towards achieving the goals. In order to achieve this, soil science has to team up with other disciplines to ensure and better different ecosystem services that contribute to the SDGs [120,121]. In this regard, the European Commission has delineated 7 soil functions that provide the link between soil and the UN SDGs (Table 1) [119].

*Table 1. The seven soil functions defined by the European Commission (EC, 2006; Bouma, 2018)*

| | ***Soil functions*** |
|---|---|
| 1 | Biomass production, including agriculture and forestry |
| 2 | Storing, filtering and transforming nutrients, substances and water |
| 3 | Biodiversity pool, such as habitats, species and genes |
| 4 | Physical and cultural environment for humans and human activities |
| 5 | Source of raw material |
| 6 | Acting as carbon pool |
| 7 | Archive of geological and archaeological heritage |

On the other hand, the ecosystem services that have an important soil component are presented in Table 2 as follows after Dominati et al. [122]. The five SDGs that have a direct relation with soil functions and soil related ecosystem services are SDG2, SDG3, SDG6, SDG13, and SDG15.

*Table 2. Soil-based ecosystem services (Dominati et al., 2014; Bouma, 2018)*

| | ***Type*** | ***Ecosystem services*** |
|---|---|---|
| 1 | Provisioning services | Provision of food, fibre and wood |
| 2 | | Provision of raw materials |
| 3 | | Provision of human infrastructures and animals |
| 4 | Regulating services | Flood mitigation |
| 5 | | Filtering of nutrients and contaminants |
| 6 | | Carbon storage and greenhouse gas regulation |
| 7 | | Detoxification and the recycling of wastes |
| 8 | | Regulation of pests and disease populations |
| 9 | Cultural services | Recreation |
| 10 | | Aesthetics |
| 11 | | Heritage values |
| 12 | | Cultural identity |

The SDG 2 (Zero Hunger) official text goes as: “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”. In this case, the primary function of soil, which is agricultural production, is of decisive importance. However, soil functions 2, 3, and 6 also play a role here as improved nutrition and sustainable agriculture forms are included in the aims of SDG2. Additionally, soil ecosystem services 1, 2, 4, 5, 6, and 8 are related to the attainment of this sustainable development goal. This makes it clear that sustainability in food system cannot be said to have been achieved unless all the environmental externalities have been considered.

In case of SDG 3 (Good Health and Well-Being), the official text goes as: “Ensure healthy lives and promote wellbeing for all at all ages”. While as good health can be characterised with more or less worldwide accepted standards, the concept of well-being can be quite personal and culturally influenced. However, it can be safely argued that good health is a vital component of human well-being anywhere. In addition to providing good food, soils have also been found to have medicinal value in different ways, for example through the production of medicinal plants but also as a source of new antibiotics [123]. In this case soil functions 1, 2, 3, 4, and 6 appear to have a significant role to play [119] while as the rest two soil functions, 5 and 7, can be said to have at least an indirect function to the human well-being. In terms of ecosystem services, all of the 12 soil ecosystem services have potential contributions to human health and well-being. In principle, the term ‘soil health’ which is now widely applied to mark the condition of soils, can be said to have a proportionate relation with human health and well-being [119,124].

The SDG6 (Clean Water and Sanitation) aims to “ensure availability and sustainable management of water and sanitation for all”. In this regard, the soil function 2 is of direct relevance while as soil function 6 contributes indirectly to the aims of this goal, as the filtration capacity of soils increases with an increase in the organic content of the soil [119]. Additionally, as Falkenmark (1997) has reported, the largest amount of freshwater in nature exists as ‘Green Water’ in the soil [52]. In terms of wastewater treatment, which ultimately affects water availability, instead of releasing it into surface waters, this water can be used for irrigation after the appropriate primary treatment has been done. For example, in Israel, currently 90% of total wastewater is used for irrigation purposes [125]. In this way, the study of different soil processes like infiltration and purification of wastewater during irrigation can also be a contribution towards achieving SDG6 [125]. Among soil ecosystem services, the numbers 3, 5, and 7 have a direct contribution to make towards SDG6.

The sustainable development goal directly related to climate change mitigation and adaptation, the SDG13 (Climate Action) urges the different signatories and stakeholders to “take urgent action to combat climate change and its impacts”. In this context, the soil function 6 is the most pertinent, while as functions 1, 2, and 3 also play a role in climate change mitigation and adaptation [125]. The measures can include increasing on-farm biodiversity, using green manure, and adopting compost use. The aims of SDG13 also incorporate the soil ecosystem services 3, 4, and 6. Similarly, for SDG15 (Life on Land), with the official text: “Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation and halt biodiversity loss”, the soil functions 1, 2, and 3 are the most relevant while as functions 4 and 7 can have varying degrees of relevance, depending on the cultural and heritage differences.

Given the centrality of soil management to the achieving of different parameters of sustainability as delineated by the UN SDGs, it is essential that efforts in this direction must be made considering these relationships. The relationships that connect soil degradation and soil mismanagement with different challenges like global warming, food insecurity, the drought-flood loggerheads, water pollution , and the massive loss of biodiversity. What must however also be kept in mind the different possibilities in sustainable agriculture that make it a perfect candidate for both climate change mitigation and adaptation [119,126].

## 2.3. Food security worldwide: an overview

As discussed in the previous sections, the natural resources of soil and water are vital for growing food for the world population. More than 70% of the food consumed worldwide is sourced from smallholder and family farms. In this regard, the stability of smallholder and family farms signifies the stability of the global food system. Secure livelihoods for smallholders hence translates to food security for the majority of the population. The Food and Agriculture Organisation (FAO) of the UN defines food security as the condition when "all people, at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [127]. In the current times, however, more than 800 million individuals worldwide do not have access to enough food while as about 2 billion people do not have access to the required quality of food, in that they have key micronutrient deficiencies, leading to the phenomenon known as 'hidden hunger' [128]. Hence 60% of individuals in low incomes countries are categorised as food insecure. Food security is not an issue of empty stomachs or unhealthy food; lack of access to food, qualitatively and quantitatively, affects the different aspects of human development—physical, emotional, social, and cognitive—and is hence detrimental to the planetary health. All of the Sustainable Development Goals (SDGs) mandated by the United Nations (UN) have a direct or indirect relationship with food security. Hence ensuring food security through sustainable food systems is vital for the overall health of the human civilisation and the natural systems that sustain it [129].

According to a recent assessment by the FAO, in terms of the Food Insecurity Experience Scale, the percentage of individuals living under general food insecure conditions ranges from 10.8% in high-income countries to 56.5% in low-income countries. On the other hand, the percentage of people living under severe food insecurity was reported as ranging from 3.1% in high-income countries to 29.5% in low-income countries [130]. The bidirectional relation of the UN SDGs and food security highlight the need to promote sustainable agricultural strategies that aim at minimizing the carbon footprint of agriculture and its impact on natural resources, particularly soil and water, in order to improve food security across societal classes across the world (Perez-Escamilla, 2017). This includes promoting agricultural practices that reduce greenhouse gas emissions, agriculture being a major contributor of the same, releasing more greenhouse gases than all forms of transportation taken together [131,132]. Large scale industrial rice farming and cattle farming are the major contributors here. In addition to this, the application of fertilizers, ostensibly to increase yields for food security, can also lead to pollution of water resources [131,133]. Furthermore, one-third of all food grown worldwide ends in waste or is lost in the supply chain [132,133]. These all factors need to be counted in when framing strategies to alleviate the problems of food insecurity worldwide.

The prediction that food supply needs to double by 2050 to meet the demands of that time and the dependence of worldwide human food narrowing down to a few food crops (with merely 20 plant species comprising 90% of the world's calories) points to the need to improve the food system, both qualitatively as well as quantitatively [134]. The current system promotes major staple crops that have been bred primarily for intensive agriculture, which are designed to maximise yields with an increase in inputs [134]. The evolution of organic and agroecological farming practices offers guiding examples of how to improve the productivity of growing food, both qualitatively and quantitatively, while at the same time ensuring care of the ecosystem components like water, soil, and air. Consumers in high-income regions can also play a role in promoting sustainable ways of growing food and thus contribute to the upkeep of planetary health, by altering their choices and food habits and preferring food products that are sourced sustainably [129,135].

The land associated challenges of our times, meaning the challenges in which land management and the way food is grown have a major role to play, can broadly be classified under four themes: climate change mitigation, climate change adaptation, combatting land degradation of various types, and ensuring food security. Perez-Escamilla (2017) referred to them as the ‘land challenges’ and assessed the potential of different land-management practices and their contribution towards meeting the four challenges. Different land challenges are related to each other, in ways that a change in one practice related to a particular challenge can have positive contributions with respect to other challenges, hence necessitating a transformative systems change in the food growing system [136,137]. Some of these practices could have cascading effects on solving different land related problems. For example, increased food productivity can one hand reduce food insecurity and on the other hand decrease the demand for land use change, which can in turn lead to conservation of natural vegetation and biodiversity, which can contribute to climate change mitigation and adaptation [129,135].

The mitigation potential of increased land productivity, as stated above, is however a function of the methodology employed to achieve that, as a function of crop type, cropping system, fertilizer management, soil management, and soil type [138,139]. If the productivity is a result of an increase in agrochemical inputs, it could have adverse effects on the environment. However, if the improvement in agricultural performance is achieved through sustainable means, emissions' savings in the range of 13 Gt CO2eq per year could be realized [140,141]. The emissions' savings as a result of non-conversion of grassland to cropland is an added aspect in this regard, given that conversion into croplands leads to an average loss of 36% of soil carbon stocks over a period of 20 years [142].

Sustainable intensification also involves the sustainable use of other agricultural inputs like the water used for irrigation. Water management practices in combination with other land management practices, for example soil carbon conservation with cover crops, can improve the soil water retention capacity. Such integrated management practices can lead to an increase in water-use efficiency by 30%, yields by up to 37%, income by up to 40%, and greenhouse gas emissions' savings by up to 25%. The savings in GHG emission through the reduced energy consumption in irrigation is an added benefit [143]. An increase in agricultural productivity can also be achieved through agricultural diversification, which is being promoted as an important land-based climate change adaptation option [138,139,144]. Crop diversification can not only improve the global food system from a supplies perspective but it can also have a wide range of benefits, which include combatting malnutrition and over-nutrition, in addition to combatting hunger [134]. In addition to increasing the socioeconomic resilience of the farmers through income diversification, it can also improve the resilience of crops by suppressing disease transmission and buffering against the effects of extreme weather events [145]. This integrated land management and diversification of agriculture is estimated to benefit at least a 1,000 million people, many of whom live from subsistence agriculture and are highly vulnerable to climate change [134,135,138,144,146].

In case of smallholder, low-input agriculture, the incorporation of legumes in the cropping system could be a way to diversify agriculture. In addition to providing a high protein diet component, legumes also contribute to the nutrition of crops by fixing atmospheric nitrogen [134].. This could be achieved through intercropping, cover cropping, or rotational cropping systems. Recent studies suggest that government and non-government organisations are increasingly favouring such interventions in agricultural diversification [147,148]. In this regard, the United Nations declared the year 2016 as the 'International Year of Pulses'. These initiatives need to be kept up and accelerated with policy support that promotes smallholder farmers as the frontline candidates to feed the world [134].

### 2.3.1. Ecological costs of the Green Revolution in South Asia

The input-intensive modern agriculture heralded by the Green Revolution (1960s-70s) has been associated with an increase in food production [298,299] (Farmer, 1986; FAO, 1961-1998) that is ultimately credited with saving millions of people from hunger, especially in South Asia. The increases have mostly been in wheat production, with rice production having shown relatively lower extent of yield increases [298]. However, the increase in the application rates of fertilizers and agrochemicals as mandated by Green Revolution practices came with problems of their own. In addition to the correlation of higher productivity with high chemical input, environmental degradation and effects on human health have also been found to be linked with high chemical inputs in different countries [300].

As is evident from the previous discussion, the successes of the Green Revolution has been directly linked to the large quantities of agrochemicals that need to be applied. It has been reported that this 'miracle technology' is incomplete without fertilizers and pesticides and that its full benefits cannot be achieved just with the farming of the high yielding and hybrid varieties. In South Asia alone, between early 1960s and the mid- 1970s, the fertilizer application in rice farming alone increased sevenfold [301]. And this was followed by extending this trend of increasing agrochemical inputs to other crops in the 1980s and 1990s. In these three decades (from 1961-1996), characterised by the widespread adoption of Green Revolution practices, nitrogen fertilizer consumption in agriculture increased 41-fold, with Pakistan, Nepal, and Bangladesh having shown even larger increases. Similarly, phosphate and potash fertilizer consumption increased 49-fold and 37-fold in India during this time; in Pakistan, while as potash consumption increased by 31 times in this time period, phosphate fertilizer consumption recorded an astronomical increase, increasing 839-fold. The trends are similar for Bangladesh, Nepal, and Sri Lanka [299].

The use of pesticides has also shown a phenomenal increase in this time period, coinciding with the adoption of Green Revolution practices and strategies [300]. This has been attributed to the weaker resistance of Green Revolution varieties to pests and diseases [302,303]. The fact that monocultures were preferred under this new framework and intensive cultivation was prescribed, the incidence of pests and diseases in agricultural fields also intensified. The import of non-local varieties, that had little natural resistance to local pests and diseases and the possible annihilation of natural pest predators by broad spectrum chemical pesticides also contributed to the same [304]. In comparison to fertilizers, the data on pesticides consumption is not easy to obtain [305]. The reported data shows that the pesticide consumption increased by more than 2.5 times (from 31,361 metric tons to 84,700 metric tons) in just over 15 years from 1972 to 1988 [300].

The large amounts of chemical fertilizers and pesticides applied in agriculture had led to the phenomenon of agricultural pollution, due to which the agricultural environment has been affected mainly with nitrates and pesticide residues. This has also led to a decline in the productivity of crops (18). Continuous application of agrochemicals also leads to a stock up of the chemicals in soil, resulting in the leaching away of essential soil nutrients like zinc and boron [300,306,307]. A decrease in the yield of crops like rice, wheat, and maize as a result of such micronutrient deficiency in soils has also been reported [306]. This leads to a feedback effect which increases the need to apply even larger quantities of fertilizers, thus increasing the input costs for farmers, while as the yields remain the same. As an example of this, IRRI has reported that in 1994, farmers applied up to 40% more fertilizers than ten years before for the same amount of rice. Acidification of soils and faster loss of organic matter has also been attributed to chemical-intensive monocultures [300,308].

The use of pesticides has also been associated with a decrease in crop productivity, albeit indirectly. High yielding and hybrid varieties have traditionally been found to be more vulnerable to pests and diseases, and the use of pesticides has led to an increase in the virulence of crop pests [306,309,310], mainly due to destruction of non-target species that include natural pest and parasite predators [304,311–314]. Proliferation of minor pests into causatives of major pest outbreaks has also been widely reported, associated with prior use of insecticides [315,316]. An example of this is the brown planthopper outbreak in the 1970s-1990s in Asia, which led to losses due to destruction of millions of hectares of rice. Under a no insecticide condition, planthoppers are controlled by wolf spiders and other natural predators on field, which are decimated by pesticides used on rice [317,318]. The graduation of white backed planthopper from a minor pest to a serious one thanks to the application of insecticides has posed serious problems in rice farming in several south Asian countries like Pakistan, India, Nepal, and Bangladesh [319]. A link between the increase in the application of nitrogenous fertilizers and proliferation of pests and diseases in rice has also been established in different studies [311,318,320].

## 2.4. Rice cultivation and Food Security in South Asia

### 2.4.1. Rice cultivation and ecosystem services

Rice (Oryza sativa) is a major food crop and is the world's most widely consumed staple food. According to FAO, rice is grown in 112 countries of the world, in different climatic conditions from temperate to tropical, spanning over 160 million hectares [149]. Rice, wheat, and maize are the main cereal crops consumed worldwide. Rice is however arguably the most popular food crop worldwide, with a unique word translation in 80 languages [150]. However, the importance of rice in global food security as well as poverty alleviation is evident from fact that in many low and medium-income countries, rice is the major staple food as well as a source of livelihood. It is the staple food to more than half the world population and provides about 25% of the global energy consumption. The global calorie consumption from rice has seen a marked increase in the last few decades, going from 391 to 541 kcal per person per day from 1961 to 2013. In the last decade, much of this increase has been observed in Africa but Asia still remains the region with the highest rice calorie consumption, at 780 kcal per person per day [149]. One reason for the popularity of rice is that it is consumed as whole grains and has considerably higher carbohydrate and protein content than, for example, maize, millet, and cassava[151].

The global rice production was 740 million tonnes in 2016, almost 90% of which was produced and consumed in Asia [149,152]. In addition to being important as a food, rice production systems provide livelihood for more than 144 million farming families [152]. With growing population, the demand for rice is increasing, especially in sub-Saharan Africa [150], while as the contribution of Africa to global rice production is still very low, at 3.3.%. However, the problems associated with rice are not restricted to its yield; problems of malnutrition, micronutrient deficiency, and overweight have been found common with rice consumers. On the other hand, monocropping systems enjoy a monopoly when it comes to growing rice, resulting in reduced on farm biodiversity [150]. In this context, a diversification of rice farming systems presents itself as a timely intervention, increasing on farm biodiversity on one hand and the nutrient content of rice on the other, in addition to aiding in the nutrition of the plants [7,134,145].

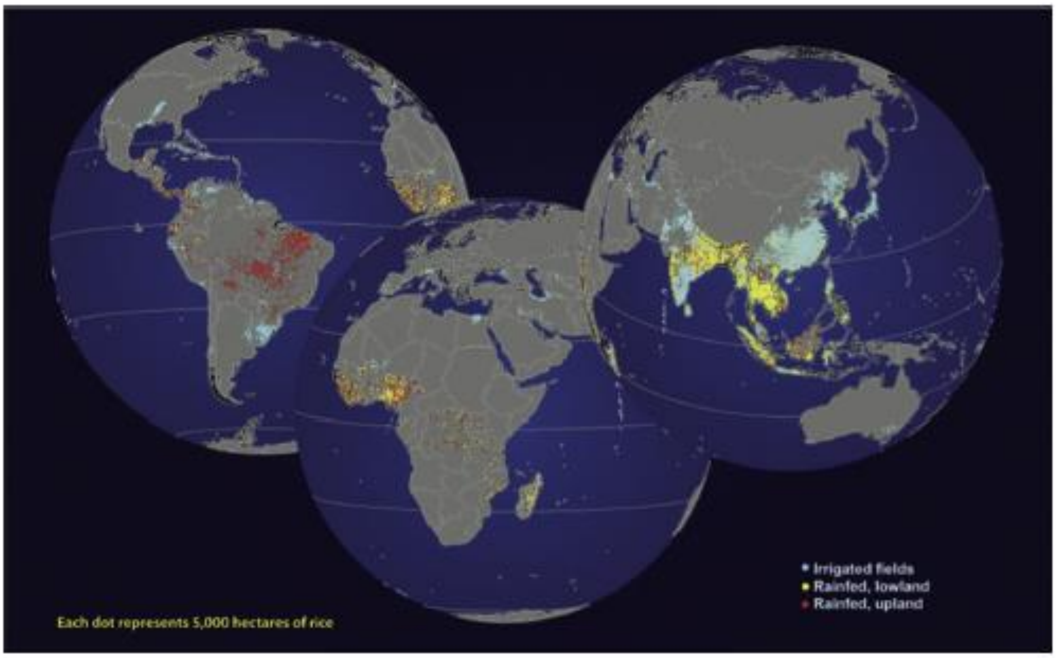



*Figure 12. Major rice growing areas in the world; irrigated in light blue; rainfed-lowland in yellow; rainfed-upland in red (GRiSP, 2013)*

Rice farming has traditionally been done in regions with abundant water supply, owing to its large water footprint of around 2-3 times that of upland crops. Of the total 160 million hectares under rice cultivation worldwide, 58% of the land area is irrigated while as 33% is under rainfed lowland, and the rest 9% is upland rice ecosystem (Figure 12). The produce contribution of these three different rice ecosystems are rather skewed in favour of irrigated rice, being, 75%, 19%, and 6% respectively [152]. Alone in this context, with better management strategies in rainfed lowland and upland rice systems, the total global rice production can be increased by 30%, taking the irrigated rice efficiency as the target. Irrigated rice systems employ continuous flooding of the field and are intensive monocropping systems heavily dependent on fertilizers, pesticides, and herbicides, which does not make it an ideal candidate when it comes to environmental concerns and biodiversity. For example, the nitrogen fertilizer losses have been found to be the higher in paddy rice systems, compared to wheat and maize. Nitrogen losses due to ammonia volatilization up to 60% of applied nitrogen have been reported in paddy rice systems [153].

Rice is native to Asia and Africa, the two continents that together house more than 75% of the world population. More than being a source of food and livelihood, rice has become an integral part of the cultural inheritance in different regions of the world. In Japanese, the word rice is used to mean a complete meal: ‘gohan’, while as in Kashmiri the word for cooked rice ‘batteh’ is used refer to the lunch and dinner meals. Rice is considered divine in many Asian cultures, with Indonesians referring to it as ‘Me Posop’ (Mother Rice), while as in the Philippines, rice is known as 'gatas ng langit' by the Aetas people, which translates to breast-milk from the heavens. In the South Asian region, a single variety of rice based dish, the biryani, has more than 20 regional variants, including those with beef, mutton, chicken, prawn, fish, eggs, or even vegetables. It is seen as a long lasting cultural communion of central Asian and south Asian cuisines, cutting across the different religious, ethnic, and linguistic barriers [154]. In some regions, the sharing of this rice based dish called biryani on Muslim festivals of Eid al-Fitr and Eid al-Azha forms an important part if the celebrations. Rice cultivation can also have subsidiary purposes, as is the case in the Kashmir valley, where the rice straw is used either as livestock feed or as a packaging material for horticultural products like apples. It is almost a closed loop. As soon as rice is harvested, the horticultural growers take away the straw as soon as the rice is shredded. This also takes mitigates some effects which rice cropping has on air quality in countries like India and China, where the burning of rice straw causes smoke that affects millions of people in big cities like New Delhi and Beijing [150]. The issue of methane emissions is another challenge for rice farming. Methane is a greenhouse gas with a global warming potential 25 times greater than carbon dioxide. It is produced in anaerobic conditions during the flooding of rice fields. The extent of this challenge can be gauged from the fact that India and China contribute about 22% and 19% of the global methane emissions [132], with rice farming contributing 11% of the global methane emissions [150]. In this regard, better water management strategies like the alternate wetting and drying (AWD) in rice farming system have led to a decrease in the methane emissions [155].

Flooded rice systems also have an associated health risk, particularly in tropical and sub-tropical regions, in terms of potentially aiding the proliferation of water-borne diseases like malaria and Japanese encephalitis [156]. In this regard, more than 137 species of mosquitoes, many of them potentially transmitting the above mentioned diseases, that breed in flooded rice paddies have been recorded worldwide [156,157]. The flooding of paddies during rice farming has another potential risk, which is associated with food safety in terms of toxic residues of pesticides and metalloids/metals like arsenic, cadmium, and mercury. These can be a health risk particularly when rice forms a large percentage of the diet, which is the case with South Asia. Hence arsenic pollution is a widespread concern in the Bengal and Punjab regions of South Asia, which straddle the Bangladesh, Pakistan, and India [158–161]. In this regard, it has been reported that aerobic water management in rice systems is expected to reduce the risk of arsenic uptake in the crop but could exacerbate cadmium uptake [162]. Pesticide residue in rice has been reported to result from the application of pesticides in the late cropping season [150].

The productivity of rice farming systems has increased in the last 5 decades, in the Green Revolution, which was accompanied by a massive increase in the application of fertilizers and agrochemicals in intensive rice monoculture. While as this increase in productivity contributed to increased food availability, it was associated with environmental degradation and greenhouse gas emissions. The potential of rice farming systems in different ecosystem services including nutrient cycling, carbon sequestration, climate mitigation and adaptation, and biodiversity conservation is huge, which remain untapped in the absence of the necessary adjustments and changes in the way rice is grown, in the was soil, water, and plants are managed in rice farming systems [150].

### 2.4.2 Rice in South Asia

The South Asia region comprises of the countries of Afghanistan, Pakistan, India, Nepal, Bangladesh, and Bhutan, in addition to the contested region of Kashmir lying towards the North of India and East of Pakistan. It is the world's most densely populated region, housing close to 2 billion people, which is around one-fourth of the world population, with an area that is only 3.5% of the world's surface area. Despite having a period of marked economic growth in the past 2 to 3 decades, depending on the country, this region still has the distinction of being the 2nd poorest region in the world with more than 500 million people living with an income of less than 1.25$ a day [163] (the poverty threshold was revised in 2015 and increased to $1.90 per day). In terms of food security, the region is home to the largest population of undernourished people. It has been reported that the situation could have been much worse in absence of the Green Revolution, which steered improvement in the food security in South Asia, primarily with the use of high yielding varieties of rice. Rice has played an indispensable role in improving the food security as well as livelihoods in South Asia, and has the potential to further contribute in this direction, given that in the face of current day challenges like water scarcity, soil emergency, and climate change, a rethink of different agricultural practices is needed [163–165]. In Asia, generally, stable prices of rice have been directly linked to food security as it forms the staple food for more than 50% of the population [166,167]. In South Asia, however, this percentage is even higher, at 70% [167], making it the most rice dependent region in the world in terms of population, in addition to being the second largest rice producing region in the world, 41% of its arable land under rice cultivation [168]. Thus, improving rice production as well as improving the ecological performance of the rice farming system is an effective approach to ensure food security as well as tackle ecological challenges in South Asia [163].

In India, rice farming covers a quarter of the total cropped area and contributes 42% of the total grain production and 45% if the total cereal production. In Bangladesh, the world's sixth largest rice producer, rice farms form almost 80% of the cultivable land and rice constitutes 92% of the annual food grain production. Pakistan is the world's fourth largest producer of rice even though its staple food is wheat. As of now, only India and Pakistan are self-sufficient in rice in South Asia; the annual import of rice was 1.84 million tons in 2011 [163]. Agriculture in general has a significant effect on the GDP of south Asian economies and rice forms an important aspect of the same. About 60% of the labour force in South Asia find their employment in agriculture while as agriculture contributes 22% of the regional GDP [169] (Figure 13). The contribution of rice to GDP however is on a decline in South Asia, having contributed 8.4% of the total GDP in 1961, which declined to 2.7% in 2007 [163].

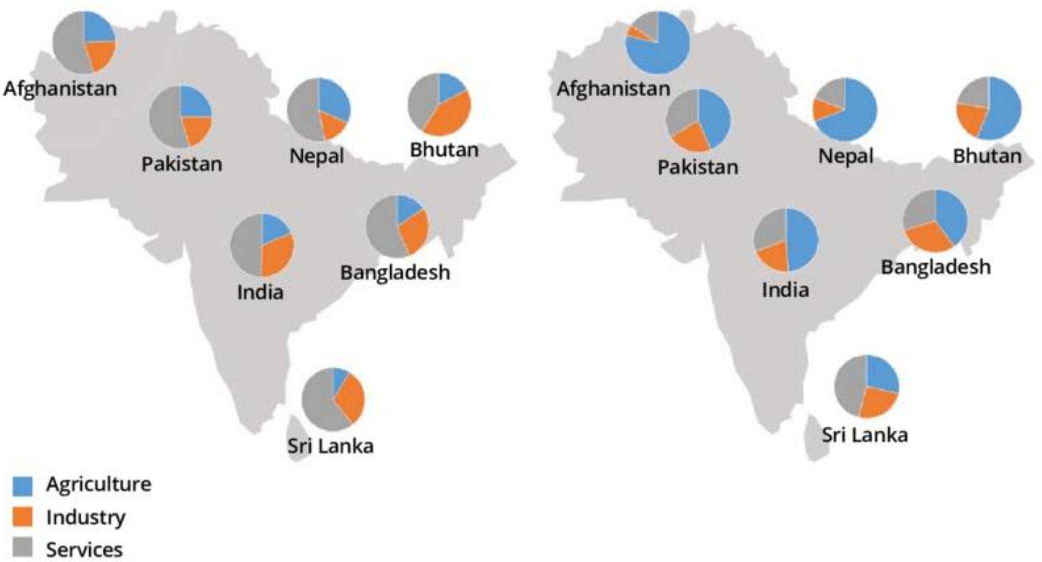



*Figure 13. Relative share of agriculture, industry, and services in GDP and employment in South Asian countries (World Bank, 2016)*

Given that rice provides up to 70% of calories and up to 55% of proteins in the diet in South Asia, the importance of rice cannot be understated, with the population predicted to exceed six billion by the end of the century. This has to be seen, also in view of the challenges like water scarcity, soil degradation, agrochemical misuse, and poor infrastructure. Agricultural economy is basically rice economy in South Asia and gaining self-sufficiency in rice production can essentially translates to achieving national food security in the different south Asian countries. It can be argued that the proportion of undernourished people globally has declined, however it would be reductionist to use this number as an indicator of global prosperity because of the substantial variation across regions [26]. Agricultural research in South Asia since the 'Green

Revolution' has mostly focussed on increasing the yield of rice and wheat through technological interventions and it has been successful to meet the regions food production goals [21]. However, South Asia is home to 28.3 and 24.5 million stunted children in the dominant rice wheat farming system and the rainfed mixed farming system respectively. Among the top ten farming systems based on the number of stunted children, in fact, South Asia is home to five of them. Clearly, the focus needs to be also on the nutrition and not just the yield [26,163].

Smallholder agriculture is the focus of the current agricultural forums at national and international levels, after their initial neglect in the early years of agricultural research [26]. The International Fund for Agricultural Development (IFAD), which was set up in the 1970s has kept supporting smallholders as its strategic priority because of the fact that smallholder and family farms provide the bulk of the consumed food worldwide [170]. In this regard, the UN declared the year 2014 as the International Year of Family Farming. The international research umbrella organisation CGIAR (Consultative Group on International Agricultural Research) also reviewed its strategy in 2008 and renewed focus on poor farmers' needs [171]. Smallholder farming should not just be classified as such on the basis of land holding; it has been described as the type of farming which is done under a general scarcity (smallness) of resources, which barely satisfy the farmers' basic needs [170]. On a land holding basis, however, anything below 2 ha is considered smallholding. However, in South Asia, the threshold is much lower than this global standard. Worldwide, there are an estimated 500 smallholder farms (and families), which lead to the full-time or part-time employment of about 2.5 billion people, in addition to providing food for 80% of the population in Asia and Africa [64,172,173]. In South Asia, smallholders constitute at least 75% of the total number of farmers [174] and it is common that women take major responsibility in producing food, in different roles, in this scenario [175]. It is a paradox, though, that smallholders, despite contributing majorly to the global food production and consumption, are net buyers of food and constitute the majority of world's economically poor and undernourished population [132,170,176,177]. This is the reason empowering smallholders with sustainable and less input-dependent strategies of farming is important to achieve the goals of eradicating poverty and hunger from the world and to maintain global food security; in fact there is no other example of rural and agricultural development that works better in this direction [177,178]. It is estimated that at least 50% of the food needs of the world population in 2050 will be produced by smallholders [179]. In terms of reducing poverty, smallholder agriculture is expected to have major impact in the regions of sub-Saharan Africa and South Asia [180].

However, the interventions in smallholder agriculture in the global South need to move beyond the ‘green revolution’ thinking of the 1960s and 1970s. Although, the Green Revolution did lead to increase in agricultural productivity, many of the interventions led to severe environmental degradation, the effects of which are being felt currently [173]. As a result, the food security challenge in our times is as big as it was 50 years ago, but we can no longer avoid the aspects of climate change induced complexities and sustainability requirements. The deceleration of yield increases over the past five decades is also a matter of concern and puts into question the gene-manipulation and input-intensification based strategies of yield improvement in the context of increasing food needs, while at the same time maintaining the health of ecosystems [181]. Hence, across some regions, new agricultural strategies need to aim at increasing the productivity generally as well as offsetting the climate-related and degraded resources-related yield losses [177]. This points to a renewed focus on the areas of climate change adaptation, on farm biodiversity, crop diversification, natural resource management, and sustainable intensification [170,172,173,182–187]. The focus also need to be put on agroecosystems with degraded soils, which could not benefit from green revolution interventions, which were more suited for favourable conditions. The Indian Council of Agricultural Research (ICAR) has included ‘halting land degradation and rehabilitating degraded land and water resources’ as a top research priority, accordingly [188]. It is pertinent to note here that the incidence of weeds in rice farming system is one of the single largest sources of yield losses and represent 6.6% of the yield gap in South Asia [26]. In this regard, agroecological strategies like the System of Rice Intensification (SRI) that aim at rebuilding degrading ecosystems and making the best use of existing capabilities of the soil need to be made more common, preferably through farmer-participatory research in South Asia [174].

## 2.5. Agriculture in climate change adaptation and mitigation

Agriculture is one of the vital human activities which contributes to, and is affected by climate change. The concentration of different greenhouse effect causatives like water vapour, methane, carbon dioxide in the atmosphere have a strong relationship with agricultural activities. And in turn the indicators of climate change like irregular weather patterns, increased frequency of extreme weather events, and temperature extremes in summers affect agriculture and hence by extension the food system. It is thus imperative that the measures to adapt agriculture to the new climate realities be taken together with the measures that mitigate the effect of the different agricultural activities on the climate and environment. It may appear that land based mitigation strategies might compete with land required to grow food, hence putting the SDGs of climate action (SDG13) and zero hunger (SDG2) apparently at loggerheads. Many studies have shown that climate change can affect food security severely, thus highlighting the importance of mitigation [218–221]. But this holds only in a scenario in which the current food system is not improved in a sustainable way [222]. It is possible to meet food security objectives and achieve multiple sustainable development goals, while being consistent with the Paris Agreement in terms of climate change mitigation and adaptation i.e. to limit global warming to less than 2 degrees and pursue the goal of 1.5 degrees above pre-industrial level [222].

However, it is possible to reconcile the seemingly conflicting interests of land-based mitigation per the Paris Agreement and food security. Broadly, the measures in this direction can be framed under the heading of closing the yield gaps in regions where the food growing potential of different farming systems is limited due to different biotic and abiotic factors. This can be achieved through improved soil nutrition, better management, and more efficient irrigation [141,223,224]. On the other hand, it is often argued that to achieve the land based mitigation targets, large scale afforestation needs to be done, which in turn can affect food security because of the associated land use change [225,226]. However, in this scenario food forests or agroforestry systems can be an integrated solution. These interventions on the supply side can increase the efficiency of the food system and reduce the competition related to land availability between food security and land-based mitigation. In case of land-based mitigation, it is important to consider the disparity in the distribution of food-insecure people across different regions of the world while framing the strategies.

On the demand side of the food system, dietary changes and dietary diversification can also play an important role in limiting the negative effect of land use change on food security and climate change mitigation efforts [227–229]. In this regard, strong reductions in per capita meat consumption is expected in China and Latin America (30% - 40%), while as moderate reductions are expected in Russia, Near East, and OECD countries (20% - 30%), which would still keep the daily meat consumption in these regions way above the recently proposed healthy diet by Willet et al. [230]. In South Asia and sub-Saharan Africa, no meat reductions are to be expected in comparison, highlighting the added importance of sustainable intensification in mitigation efforts in these two regions. Dietary changes and diversification in the former regions where the consumption is very high can lower the requirements for achieving the targets in regions where the consumption is already low [222]. Taken together, the potential of better management practices in agriculture towards reducing global greenhouse gas emissions has been projected to be in the range of 0.3 to 1.17 Pg carbon per year, which represent 2.7 to 10.4% of the total global greenhouse gas emissions [231–235]. It is in this context that sustainable agriculture has been defined as the system of agricultural practices that meet the societal demands 'for food and fiber, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered' for the current and the future generations [222,236].

The soil linked strategies to increase the mitigation of greenhouse gas emissions include soil organic carbon build up through various means. The main pathways to increase and restore soil carbon stocks proposed by different studies include improving on farm biodiversity and increasing biomass-C input through the use of cover crops [115,237–243]. These measures also lead to an increase in the agronomic productivity of the crops. Taking the example of South American agriculture, which, a phase-wise adoption of low-carbon agricultural systems can offset up to 50% of the global annual emissions over a period of 30 years, with a potential mitigation of 8.24 Pg C. Low-Carbon Agriculture (LCA) has the potential to significantly increase food production in parallel to these mitigation contributions, indicating that with proper management practices agriculture can be an important part of the global climate change mitigation efforts and food security efforts in a synergetic manner [244].

## 2.6. The Nexus approach: Water-Soil-Food nexus

In the previous sections, the discussion has led us into a particular direction regarding the approach to be taken in navigating the bigger challenges of our times like food security (qualitative and quantitative), water scarcity, land degradation and land-use change, poverty, and climate change. The interdependence, or at least the interrelatedness of these different challenges calls for an integrated systems approach to solve the problems associated with water scarcity, soil health, and food security [245–247]. This approach that focusses on interventions that take into account the different relationships between the water, land, and food sectors can be termed as the nexus approach and the corresponding nexus as the Water-Soil-Food nexus.

The two natural resources that are essential to growing food are land and water, which are not inexhaustible. In fact, in many regions of the word water scarcity and land degradation (soil emergency) are already affecting food production, resulting in yield gaps. Studies have shown that in 'business as usual' scenario, by 2050, 40% of the population worldwide will be living in regions with not enough water and land to meet the food requirements of the population [248]. In addition to dietary changes and diversification of food, interventions that address the nexus challenges need to be put into place in our food systems. Energy is an important aspect of the nexus approach as well, but seen from a purely local community perspective[249,250], in which the focus is laid on reducing the input intensive nature of the farming practices, the approaches discussed below focus on the Water-Soil-Food nexus.

The need for a new nexus approach to food systems is evident from the numbers relevant to the issues of food, land, and water. The per capita availability of land halved (from 4360 $m^2$ per capita per year to 2280 $m^2$ per capita per year) from 1960 and 2010 and is expected to decrease 30% more to 1660 $m^2$ per capita per year by 2050 [167,170]. Similarly, the water availability has also halved in the past 50 years, from 26,100 $m^3$ per capita per year to 14,000 $m^3$ per capita per year, from 1960 to 2010 [170]. It is expected that the regions with the strongest constraints to food supply will be Asia and Africa in the coming decades. In the past, however, water scarcity projections have become a reality much before than the expected date. For example, the 2025 water scarcity projections by the International Water Management Institute (IWMI) were reached in 2000 [251]. In this regard, it is important to discuss the availability of both land and water together. Otherwise, the scenario could be the same as in some countries, where there is a stable supply of water but the available land is just not enough to fulfil the food demand [248]. The outlook for 2050 presented in a study by Ibarrola-Riva (2017) has shown that under a business as usual scenario, even with a lower population growth and no further agricultural expansion, South Asia and sub-Saharan Africa will not have either enough water or land to produce enough food to fulfil the needs of their population [248]. The analyses are however based on the current agricultural systems [252,253], where a closing of the yield gap [62] is still possible, particularly in developing countries. This means that these regions have challenges to navigate with respect to food systems more than any other region [248]. Hence, there is a need, more urgent than ever, to change the way we grow our food, with strategies that take care and take into consideration the wellbeing of our land and water ecosystem in addition to the agro-ecosystem [248].

In this regard, simply increasing the agricultural production with the available land and water resource may not be the solution, as explained above. The traditional water saving scenario by improving irrigation infrastructure have reported to have failed to restore either a groundwater balance or regional water sustainability [254] due to the practice of the 'saved' water being diverted to other purposes or expanded land [255]. As a result, the reduced the cultivation of water-consuming crops (the so called thirsty crops) has been suggested as a more effective way to resolve the global water shortage [256]. However, this may also not be very effective, given that these crops are not just any commodity; they are staple foods of people around the world. Hence the need to provide a integrated systems solutions that increase productivity, reduce water needs of the crops, and preserve land and soil at the same time. This can also help developing countries that have a far greater agricultural water footprint than developed countries to halt the rampant groundwater depletion and at least serve as a disruption to the virtual water monopoly of the industrialised regions, as crop water use, groundwater depletion and international food trade are intricately connected [257–259]. While as 13% of the water used for crop production globally was consumed in the end effect internationally and not in the region the crop was produced, three major world crops, wheat, rice, and maize, account for upto 55% of the global virtual water flow [260]. The need to focus on the less developed regions becomes more important in this regard, given that the effects of climate change on agriculture and food security are more pronounced in sub-humid tropics in Africa and South Asia [261], regions that already have a low capacity for adaptation [256,262].

The Comprehensive Assessment of Water Management in Agriculture (CAWMA) reported that the current consumptive water use in food production is about 6800 $km^3$ per year, out of which about 1800 $km^3$ is supplied through irrigation water [47,251]. With the current agricultural practices, in order to cater to the food needs of the world in 2050, an additional 5600 $km^3$ per year will be required. A small part of this additional requirement, a maximum of 800 $km^3$ can come from improvements in irrigation efficiency, while as 1500 $km^3$ per year is possible through improvement in water use efficiency in rain-fed areas. That leaves us with a deficit of 3300 $km^3$ per year[71,251,263] (Figure 14). This deficit needs to filled in through improvements in the way agriculture is done, in the way food is being grown. The use of saline and wastewater in agriculture has also been proposed [264], the practicability of which needs to be examined in view of toxic accumulation in the crops. The interventions need to focus on the land aspect of growing food as well, rather than just improving the water use efficiency. The fact that technological interventions alone cannot offset the yield gaps is evidenced from the following examples. In southwest India, in the Thungabhadra irrigation project, an estimated 15% of the system productivity was lost due to land degradation while as in Punjab, Pakistan, 1/3rd of the total factor productivity growth attributable to technological innovation, infrastructure development, and education was lost to resource degradation caused by the intensification of land and water use [259,265,266].

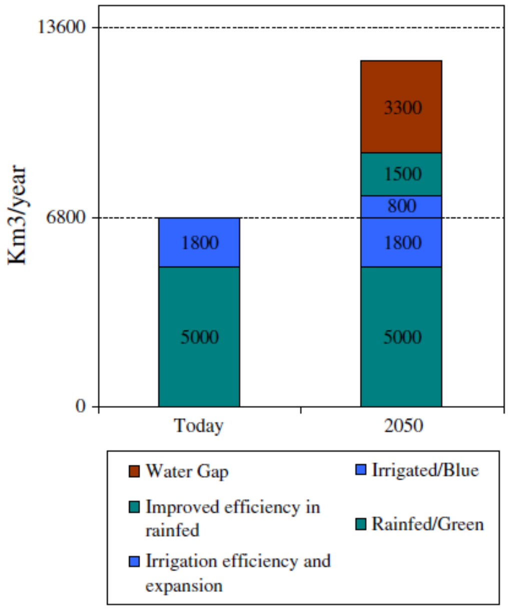



*Figure 14. A representation of the world water demand in food production projected for 2050 (de Fraiture et al., 2007; Molden, 2007; Molden et al., 2007; Hanjra and Qureshi, 2010)*

From the discussion above, we can deduce that the food crisis is as much as problem of water scarcity in arid and semi-arid regions, as much as problem of land in water-rich regions [181], and as much as worldwide problem that needs an integrated approach to sustain the support system of food for the next generations. This approach known as the nexus approach is defined as the “systemic thinking and a quest for integrated solutions to guide decision-making about resource use and development”, as defined by the Stockholm Environment Institute [267]. The domains of land and water are intricately connected through various feedback loops that ultimately affect the food production process [268]. For example, land use change can affect water quality while as soil degradation can affect the water retention capacity of land and ultimately the groundwater recharge [269,270]. Lower water quality in turn affects the ability of the soil to hold nutrients (or toxic metals) and thus its ability to produce healthy food and fiber[267]. Hence, the nexus approach aims at improving the efficiency of food production in an integrated manner by identifying the linkages across the relevant sectors of land and water[246] (Figure 15). Targeted agroecological interventions like integrated soil fertility management, alternate wetting and drying of rice fields have been listed as steps in this direction [271]. Otherwise, as the Bonn Nexus Conference 2011 declared, “this pressure on resources could finally result in shortages which may put water, energy and food security for the people at risk, hamper economic development, lead to social and geopolitical tensions and cause lasting irreparable environmental damage” [246,272].

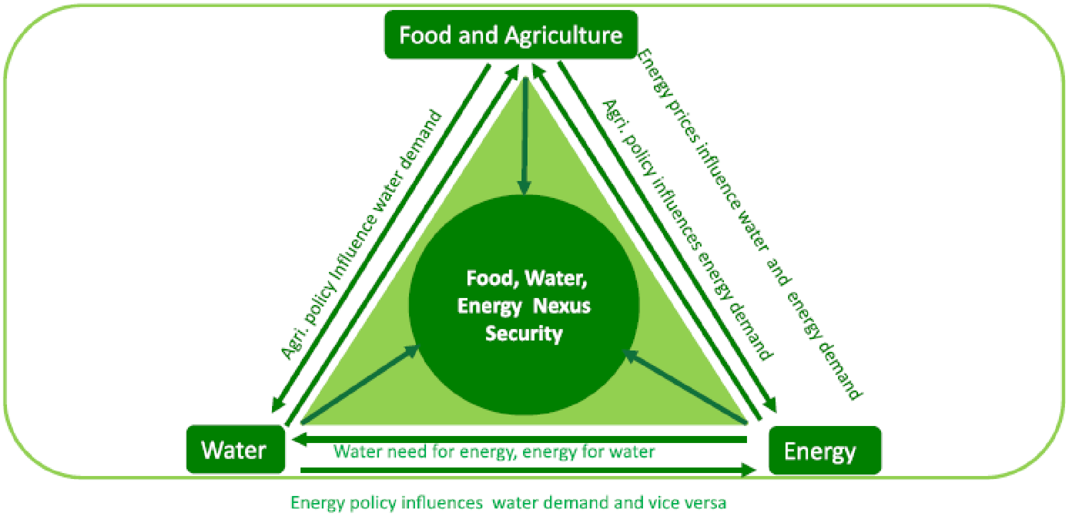



*Figure 15. The nexus relationships between food, water, and energy sectors (Golam Rasul, 2016)*

## 2.7. Water Pollution and Wastewater as Water and Nutrient Source

### 2.7.1. Groundwater and surface water pollution with agriculture

The effects of agriculture as a whole on the original pristine state of freshwater systems are widely documented. Previously, a simplistic approach of considering a fixed number of substances as pollutants and their individual effects on specific communities and components in freshwater bodies was used to quantify water pollution. A more holistic approach considers the impacts of different point and non-point sources on the ecosystem as a whole. The European Water Framework Directive has implicitly recognised this in highlighting the need to restore water bodies to 'good ecological quality' [273]. The complex relationship between agriculture and freshwater systems has been well recognised in literature since long. As early as in 1979, the Royal Commission on Environmental Pollution (RCEP) published a report entitled 'Agriculture and pollution' [274], however the focus on the pesticide residues, agrochemicals, and farm wastes as just pollutants has changed ever since. Now, the focus has shifted to their impacts on the whole freshwater system rather than just treating them as an anomaly in the composition of the water mass [273].

The impacts of the pollutants can be quantified in terms of the different ecological features [273] or functions of the freshwater ecosystem. The first among these is the balancing and cycling of essential nutrients like nitrogen and phosphorus. Second is the biological composition of the water body, specific to the climatic zone where it is located. Then there are the physical extent, connectivity, and size of the water body. In a pristine state, these ecological features of a freshwater body are self-regulating. However, any change to these features requires corrective measures, like when residues from agricultural practices end up in the water bodies, disturbing the nutrient balance and as a result affecting the biological composition and biodiversity of the same [275–279]. Essentially, pollution exacerbates the risk of damage to a natural ecosystem and affects all associated and related living beings. There have even been studies linking agricultural practices with the increased incidence of diseases caused by water-borne vectors [280,281]. However, the very nature of uncertainty [282–286] in quantifying precisely the effect of different agricultural activities on the different ecological features of a water body has been weaponised in order to delay the regulation of agricultural activities [273].

With a further increase in food needs projected for the next decades, these processes are expected to pick up pace, with the current agricultural practices. The projection for the next 50 years suggests that a further $10^9$ hectares of land (natural ecosystems) worldwide will be converted into agricultural land [287], if the business as usual scenario of growing food is continued, leading to up to three-fold increase in the eutrophication of water bodies [288]. Hence the challenge here is to redesign our agricultural systems to minimise the damage as well as to ensure a secure supply of the land-based products [273] like food, fibre, and meat. In this regard, the classical approach to economics of Adam Smith is increasingly being referred to as flawed and environmental damage and environmental benefits are no longer disregarded as simply ‘externalities’. The same applies to natural ecosystems whose value, although difficult to quantify, may well surpass that of modern systems of production [273,289,290].

### 2.7.2. Wastewater as a Nutrient and Water Source

The water and nutrient needs of the farming systems are the basic needs that enable a land mass to grow healthy and nutritious food. Yield gaps in different farming systems in different regions of the world lead to insufficient food supply, with water scarcity and the loss of nutrients in the soil being the main reasons for the same. Wastewater is increasingly being looked at as a potential input material for agricultural production, be its direct use or indirect use. By direct use, the use of suitably treated wastewater is meant, while as the indirect use can also mean use of wastewater for growing non-food energy crops on polluted land areas where food crops cannot be grown (Reference), which in end effect increases the availability of freshwater for food crops.

A recent study presided over by the United Nations University [291] gives insights into the global potential of wastewater as a water, nutrient, and energy source. According to this study, about 380 billion $m^3$ of wastewater are generated worldwide, annually [291]. This number is equal to

21% of the total annual irrigation water consumption in food agriculture, which is 1800 billion $m^3$ [47,251]. The worldwide wastewater production is expected to increase by at least 50% by 2050 over the current levels (Figure 16). The nutrient load of the three essential plant nutrients nitrogen, phosphorus, and potassium in the global wastewater stream would offset 13.4% of the global demand in agriculture, with their respective quantities embedded in the wastewater being 16.6 million metric ton, 3.0 million metric ton, and 6.3 million metric ton respectively.

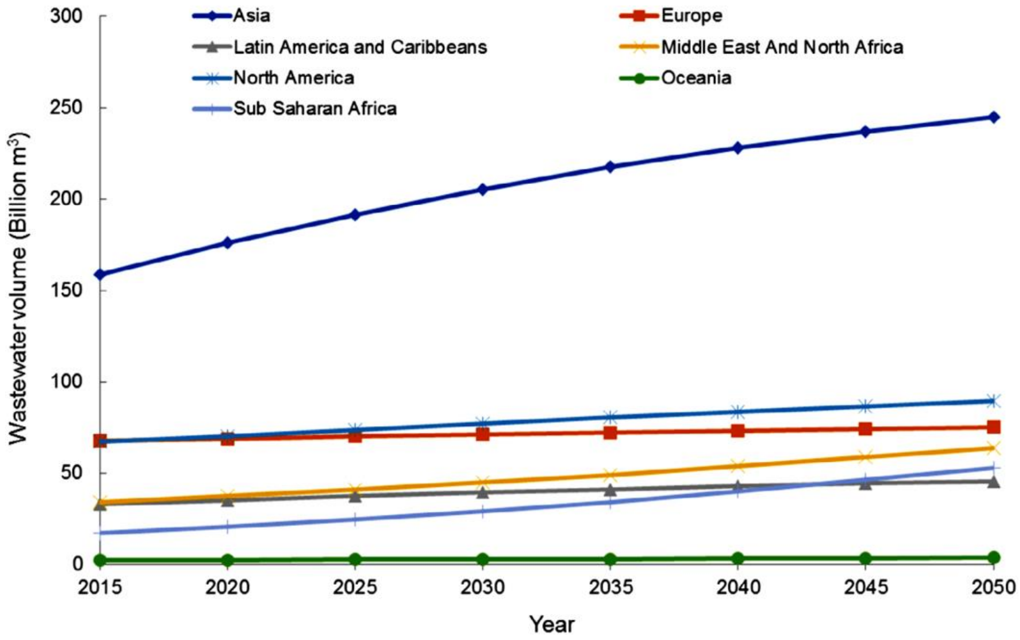



*Figure 16. Projection of wastewater volumes in 2050 in different regions of the world (Qadir et al., 2019)*

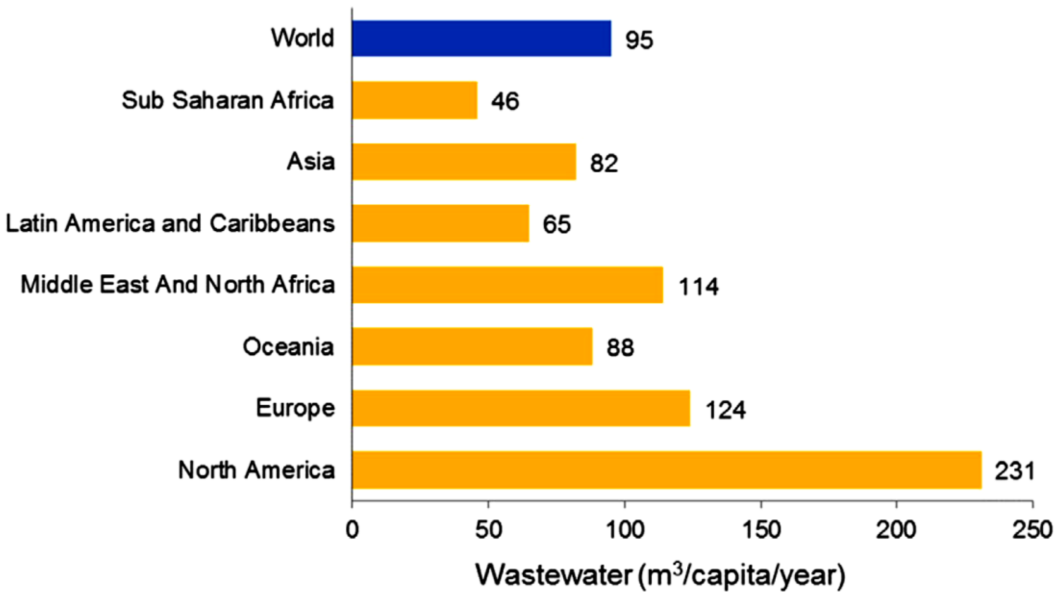



*Figure 17. The average per capita contribution of wastewater in different world regions (Qadir et al., 2019)*

The plots in Figure 16 and Figure 17 point to a water monopoly that was also discussed in earlier sections [259]. While as in absolute terms, Asia is the highest producer of wastewater annually (159 billion $m^3$), in per capita terms, North America and Europe are the biggest producers with 231 $m^3$ per capita and 124 $m^3$ per capita respectively. Sub-Saharan Africa has the lowest per capita wastewater production at 46 $m^3$ while as Asia stands at 82 $m^3$, both values less than the global average of 95 $m^3$ per capita per year [291]. This adds to the already existing virtual water imbalance that works against developing countries that produce food and goods that travel through international trade and are ultimately consumed in developed countries.

In order to recover nutrients from wastewater, the recovery of nutrients can already be started at the source, the toilet in case of urine, which is known to contain nutrients like nitrogen and phosphorus in high concentrations [292]. It is worth noting here that human urine is responsible for 80% of the nitrogen loading and 50% of the phosphorus loading in the wastewater going into municipal wastewater treatment plants [293]. This approach would not only provide nutrients required in agriculture but also prevent eutrophication of water bodies and save the amount of energy needed in the running of wastewater treatment plants [294,295]. Another approach could be specific treatment of the wastewater stream keeping the nutrient requirements of soil as the effluent benchmark, using the effluent to irrigate and fertilize the soil at the same time [291,296,297].

### 2.7.4. Agriculture and Water Pollution

The excessive use of agrochemicals in agriculture has also had impacts on other components of the environment as discussed in previous sections. Eutrophication of in water bodies is an example of the same. In agricultural systems, fertilizers have been found to be responsible for the increase in the growth of weeds in rice fields, which furthers the need to use herbicides and hence perpetuates the dependence on agrochemicals and aggravating the agricultural environmental pollution [304,321]. Hence the challenge of our times is to implement agricultural strategies that are less dependent on chemical inputs and do not serve to perpetuate the ecological degradation in pursuit of higher yields [300].

Water quality issues linked to agriculture are not restricted to developing countries alone. In developed countries in the Organisation for Economic Co-operation and Development (OECD), agricultural water quality has been marked among the major environmental issues. In OECD countries, agricultural activities from crop and livestock management have been found to be responsible for the pollution of water with nitrates, phosphates, soil sediments, salt, as well as pathogens. This leads to costs associated with the removal of pollutants from drinking water supplies as well as the decontamination of rivers, lakes, and other water sources to maintain to avoid damage to different commercial, recreational, and cultural ecosystem services [322].

Although most of the OECD countries operate monitoring networks to keep track of the state of water pollution in water bodies, the monitoring of agricultural water pollution is very limited. Just over one-third member countries monitor nutrient pollution in water bodies resulting from fertilizer applications and even lesser number of countries track pollution due to pesticides. The extent of agricultural groundwater pollution is even less documented as compared to surface waters due to the costs involved in sampling. Despite the lack of extensive monitoring infrastructure, nearly one half of the member countries have reported that the concentrations of nutrients and pesticides (mainly sourced from agricultural practices) in surface and groundwater at monitoring sites exceeds the nationally approved drinking water limits, with the problem more severe in rivers, lakes and marine waters. Over the last three decades, while as the pollution due to point sources has decreased rapidly, it has only increased the share contributed by non-point pollution (e.g. agricultural water pollution), both in surface and coastal waters [322].

In a growing number of OECD countries, farmers are now increasingly adopting farm management practices that reduce the risk of water and soil pollution, as part of voluntary private-led initiatives. However, still only one-third of the member countries have mechanisms to monitor changes in soil management [322]. In this regard, changes need to be made at a policy level in the form of policy packages that encompass institutional reforms and increased community engagement aimed at addressing agricultural water quality issues and water resource management [322]. Given the vulnerability of agricultural systems and water resources to the vagaries of climate change, policies need to be increasingly responsive and adaptive to these new realities [16]. Agroecology based organic farming promises to be an important step in this direction and statistics are encouraging in this regard. Currently, 2% of the total farmland area in the OECD countries is under organic farming while as the number is higher in most European Union countries, at around 6-8% [323]. There is an increasing trend in this regard with the total organically managed agricultural area increasing by 20% from 2016 to 2017 [324]. In this regard, agriculture based on the integration of land-use and water-use management in order to conserve water, improve water quality, and to provide multiple associated ecosystem services seems to be the way forward [322].

## 2.8. The concept of the environment as a trust – *amanah*

The way human beings manipulate and exploit their natural resources and the environment is demonstrative of their beliefs, worldviews, and the cultural background. The worldview (the belief system) essentially reflects the terms of interaction with the environment [325]. It is in this regard that Nasr (1968) identified the root causes of the environmental crises as spiritual rather than anything else in his book *Man and Nature – The Spiritual Crisis of Modern Man* [326]. Timothy Winter (2020) contends that the religious case against materialism, which is characterized by consumerism and makes human beings and the planet sick 'spans the religious divisions' [327]. Hence it is practical to present the ideas of sustainability and resource conservation to people we intend to work with within an ethical (faith-based) framework they can easily relate to.

The Muslim countries' belt ranging from North Africa through the Near East to Central and South-central Asia are particularly affected by and/or vulnerable to the diverse effects of climate change, desertification, and an increasing scarcity of natural resources [328]. The overexploitation of water resources threatens the drinking water supply as well as the agricultural production in these countries. It is in this regard that the discourse around environment protection and consciousness is gaining in traction in these countries, which has manifested itself also in the form of references to Islamic environmental ethics in the Friday sermons. The central element of Islamic environmental ethics includes the love for the creation in all forms, with the understanding that all forms of creation have their own functions to perform for the proper functioning of the life system, in which every life form is interdependent on the other. All the components of the environment function in an integrated manner and play a vital role in maintaining the environmental balance in nature and in performing the essential functions assigned to them that make it possible for human beings to live in a state of good health and prosperity [329,330]. This unity of the life system in the interdependence of its various components reflects the core concept of the Islamic theology, which is the unity of God (*tauhid*) [328,331,332].

Although a concrete codified form of Islamic environmental ethics does not exist, there are directions and remarks in the canonical sources of Islamic theology (Qur'an and Sunnah) that point the reader towards a higher environmental consciousness. It has been noted that the metaphysical conception of nature in the Quran transformed the Arab superstitious and lifeless views of the natural world into a purposeful view of the creation [333]. The philosopher-poet Muhammad Iqbal, who did his doctoral studies from the Ludwigs-Maximillian University in Munich, also remarked that the apparent purpose of the first revealed chapters of the Quran seems to awaken in the reader a genuine consciousness of the different relationships between man, the Creator, and the environment at large [334]. The general Quranic paradigm seems to be the utilization of natural resources and the environment based on the philosophy of avoiding aggression and misuse, and of construction rather than destruction [332].

However, since decades the over exploitation of environment and natural resources has been continuously justified for the sake of economic development and industrial growth. This has led to grave consequences like the loss of biodiversity, desertification, soil erosion, flash floods. The loss of biodiversity in forests has been counted among the main issues in environmental degradation, in this regard [335]. With the aid of modern technologies, the exploitation of natural resources has become easier than it ever was for our previous generations. Overexploitation of a natural resource is bad not only because of the exhaustion of that particular resource but also different constituents of the natural ecosystem are closely linked and related to each other. So much so that even a renewable resource becomes so depleted that it increasingly resembles a non-renewable resource . This further highlights the need for a framework to work with that implores people at large from the perspective of the divine to preserve and protect the environment, in societies in which the divine laws play a greater role than imagined in the modern discourse. In this regard, the *Maqasid al-Shariah* (Objectives of the Islamic Law) approach ranks the preservation and protection of environment as one of the pillars of the principle of the preservation of property [336]. Izzi Dien (2000) argues that the protection to human life as enshrined in the Quran extends to include protection of all the environmental conditions that enable all forms of life to continue; right to life means right to healthy environment [337].

It is imperative in this context to mention the six terms from Quran and Sunnah that serve as anchors to the body of Islamic environmental ethics [328]:

i. *Fitra*: The natural tendency to conserve and protect the creation against harm.
ii. *Tauhid*: The unity of the creation in their interdependence as a reflection of the unity of God.
iii. *Mizan*: The balance in nature that creates a perfect life supporting system for all forms of life, which must not be disturbed.
iv. *Khilafa*: The role of the human being as a caretaker representative of the Creator, responsible for taking care of the earth.
v. *Amanah*: The trust of responsibility that has been bestowed on the human beings. This bestowed trust includes the earth, the environment, the different forms of creation—plants and animals.
vi. *Ubudiya*: The submission to the Creator, in responsibility and being answerable for actions.

It is in this framework that Quran prescribes the conservation of resources, calling upon the believers to avoid being extravagant [338], through wastage and overconsumption [328]. The role bestowed by Khilafa on the human being prohibits them from taking actions that cause manipulation or pollution in the environment and use the natural resources also keeping the needs of future generations in mind [339,340]. It has been argued that human beings have been entrusted to bear Amanah (obligation duties) of the earth by virtue of their ability to attain knowledge and intellect [341]. Mawdudi (1967) has argued that humans have been given the power to make use of the environment through the knowledge and technology and their disposal and this in itself is a divine test for human beings to see how they take care of the trust (Amanah) [342]. The concept of Amanah is hence interpreted as the obligation to conserve the trust that has been bestowed upon us in an honest and sincere way.

In the Muslim tradition, the life of Prophet Muhammad(*peace be upon him*) is considered as an example of the bonafide example that Muslims can aim to follow as the way to follow the divine commandments. There is a narrated tradition in which a companion of his was using an excessive amount of water to wash himself for prayers when he commanded him "not waste (water) … even if you are washing yourself by a flowing river" [343]ahmadah. This imperative to be mindful of consumption of water even when it is for a ritual purification for prayer highlights the importance of mindful consumption that can serve as a guide towards resource conservation and sustainability in Muslim societies [337]. Such traditions can also be extended to agricultural practices and can be utilized to spread awareness about water conserving agricultural practices. The values of trusteeship should enable people to deal with natural resources properly no matter if he or she works in an industry, in a farm, or in a forest. Hence, per Islamic environmental ethics, the protection and preservation of environment and natural resources is not just for a worldly purpose but also to fulfil the duty of having been entrusted with Amanah [332].

## 2.9. Agroecological approach to agriculture as an alternative

The agroecological approach to agriculture in general and food security in particular is being widely pushed as the way forward, given the limitations of the current industrial agriculture and the numerous challenges faced by the food systems. In the last three decades, a wider acceptance of agroecological interventions has led to projects being done in different parts of the world researching the role agroecology can play in achieving the goals of food security, sustainable development, and bio-diversity protection while at the same time giving due consideration to the aims of the global climate agreements. The following network visualisation gives an idea about the research papers published in the time period 1991 to 2020, whose subject area lay at the intersection of the topics of agroecology, sustainable development, food security, and climate change (Figure 18). In the figure, the top 29 keywords are visualised as a network map

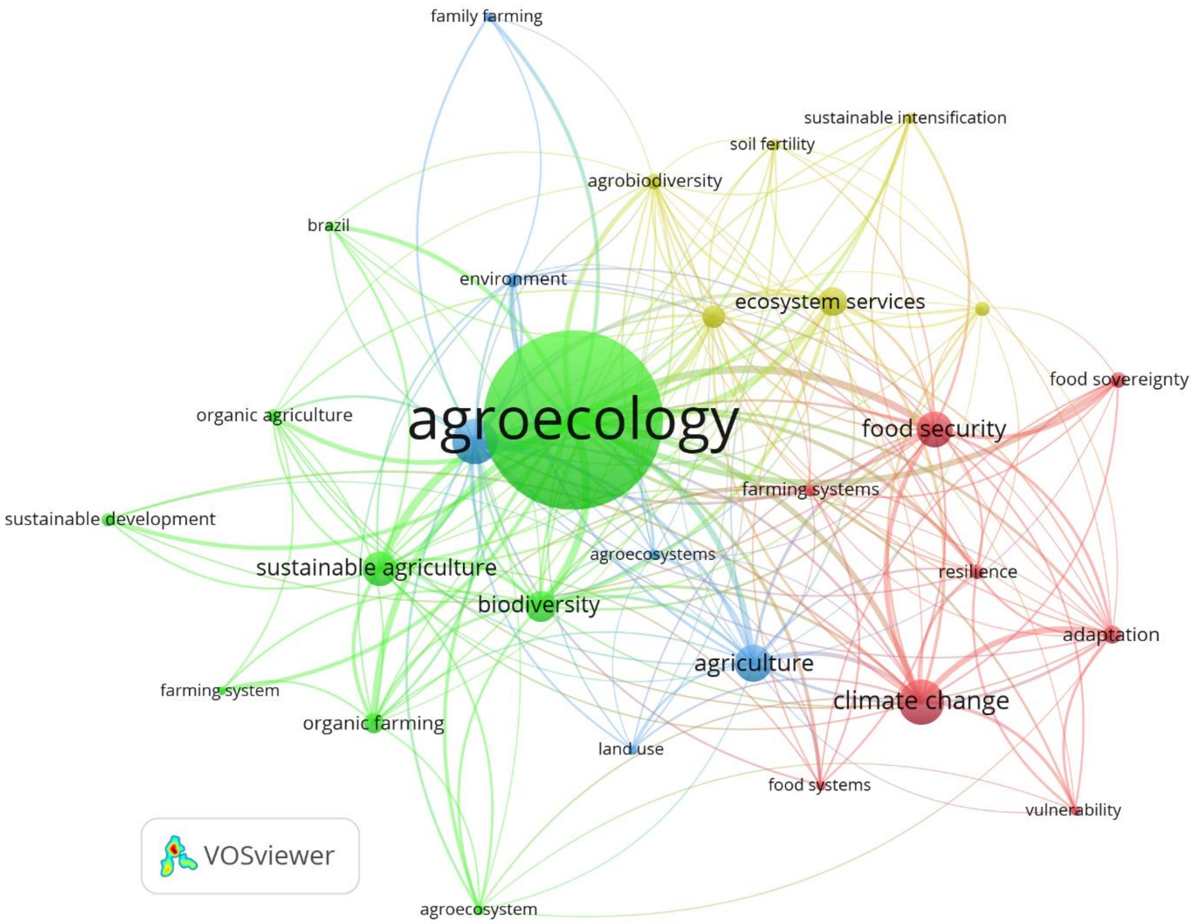



*Figure 18. A network visualisation of the top 29 keywords that have appeared in literature published in the time period between 1991 and 2020 on topics related to agroecological contributions to food security in the backdrop of climate change (VOSviewer Trial Version)*

with the help of VOSviewer software (trial version) from the Centre for Science and Technology Studies, Leiden University, The Netherlands. The subject area wise distribution of the research papers can give the reader an idea about the wide ranging relevance of agroecological interventions in the current times (Table 3). The table contains the top 10 subject areas on Scopus (Elsevier) database based on the number of research papers falling under the scope of the subject area. The following example can be a guide for the reader to make sense of the two percentage values in the table. A total of 45% papers fall under the subject area of 'Environmental Science', however some of these papers may also fall under another subject area due to its interdisciplinary nature. Hence the sum of percentages of the 10 subject areas listed can be well over 100. This also gives an idea about the cross-disciplinary relevance of agroecological interventions in the current social, economic, and ecological systems, especially the food system.

*Table 3. The top 10 subject areas of research that contain the bulk of agroecological literature in the time period 1991 to 2020 on topics related to agroecological contributions to food security in the backdrop of climate change (Scopus)*

| RANK | SUBJECT AREA | FREQUENCY | ABSOLUTE % (T = 1974) |
|---|---|---|---|
| **1** | Agricultural and Biological Sciences | 1155 | 58.51 |
| **2** | Environmental Science | 889 | 45.04 |
| **3** | Social Sciences | 549 | 27.81 |
| **4** | Earth and Planetary Sciences | 205 | 10.39 |
| **5** | Energy | 179 | 9.07 |
| **6** | Engineering | 123 | 6.23 |
| **7** | Biochemistry, Genetics and Molecular Biology | 112 | 5.67 |
| **8** | Economics, Econometrics and Finance | 98 | 4.96 |
| **9** | Medicine | 55 | 2.79 |
| **10** | Arts and Humanities | 48 | 2.43 |

As discussed in the previous sections of this chapter, the importance of rice cultivation is of worldwide importance. However, the current input-intensive framework in which rice farming is done currently is neither ecologically and economically viable for the smallholder farmers, nor does it cater to the projected increases in the food needs of the generations to come. The sustainability aspect of the current rice cultivation system is in stark focus in this study. In this regard, the negative effects of the agrochemical-intensive rice farming systems on the land, water, and air ecosystems has been discussed in the previous sections. As a result, the need for alternative practices that are both sustainable and gainful for smallholder farmers, who are the main producers of the food consumed worldwide, looks ever more crucial. In this regard, agroecology has been proposed as the guiding principle to achieve world food and nutrition security through sustainable means by no less than the United Nations itself [344]. The global COVID-19 pandemic has only reinforced the urgency that is needed to carry out a paradigm shift from industrial agriculture to diversifed agroecology-based agricultural systems [17] (Figure 19).

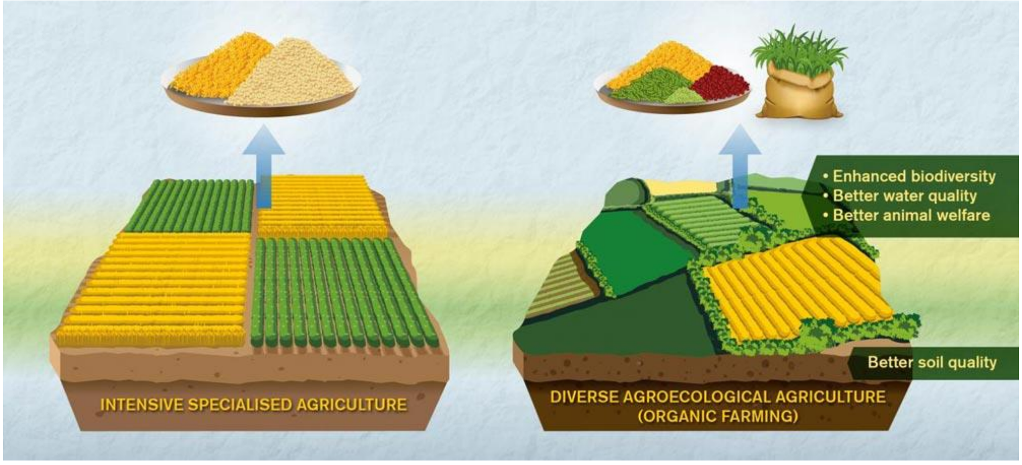



*Figure 19. A graphical representation of the different 'yields' (benefits) of intensive monocultures and diverse agroecological agriculture (Yen Strandqvist, Chamlers University of Technology)*

The System of Rice Intensification (SRI) is an agroecological set of practices that presents an alternative to the currently dominant method of growing rice under flooded conditions. SRI is reported variously as an agro-ecological, climate-smart, water-efficient, and a resource-conserving methodology of growing rice. The inclusion of the term ‘intensification’ in the name does not allude to any increase in the input, in the industrial agriculture sense of the word. On the contrary, there is less input of seeds, water, and agrochemicals in rice production with SRI. SRI consists of practices give more consideration to the proper management of the resources associated with rice cultivation—seeds/plants, soil, water. The SRI method has shown potential in reducing the ecological costs of rice farming while at the same time increasing the gains for farmers in general, and for smallholder farmers in particular. Under SRI, the water use in rice farming can be reduced by up to 50% and the yield can go up by up to 200%. The SRI methodology has been adapted to different agro-climatic zones and also other crops like wheat, maize, and sugarcane, under the rubric of the System of Crop Intensification (SCI) [186,345–348].

The System of Rice Intensification is characterised by a few farming practices that set it apart from the traditional flooded rice farming system. Starting from first stage of rice farming, the nursery; under SRI the nursery is not kept under flooded conditions unlike the conventional system. The rice seedlings are transplanted at the two-leaf stage (8-14 days age) as compared to 4-5 weeks under the conventional system. In SRI, instead of planting multiple seedlings at one place, seedlings are transplanted singly and at a wider spacing (25-30 cm) in a square pattern. Once transplantation is done, the rice field is not kept flooded with water and rather irrigated based on need (alternate wetting and drying). Another practice that is unique to SRI is the manually operated weeding that is done in the first few weeks after transplantation, instead of using chemical weedicides. These different practices serve towards the better management of soil, rice plants, and water in the framework of rice farming system. As a result of this better management of the different resources, studies have shown farmers achieving better results in terms of the crop yield, primarily. SRI is a subject of increasing interest in rice research. Although, different studies have pointed to an increase in the productivity of rice under SRI, employing the alternate wetting and drying (AWD) method of irrigation, it ensures increased dry periods in the rice cultivation time. As a result, there is an increased occurrence of weeds, competitors to the rice plants, under SRI. This is one of the major reasons that leads to an increased labour requirement in SRI in the form of manually operated weeding, which forms one of the common critiques of SRI from a socio-economic perspective [181,349,350]. Agroecological crop management is also vital to enhance the micronutrient content of the soil and by extension tackle the problem of micronutrient deficiencies in the human diet [128]

However, SRI also provides room for other agroecological practices like intercropping and mulching to be introduced in rice cultivation. These practices are not possible in true sense under traditional flooded method. SRI, with wider spacing between the plants and alternating dry and wet periods without flooding provides an ideal space for an intercrop. Intercropping also promises to address the common criticism of SRI viz. growth of weeds under dry conditions and the resulting increased labour in weeding, as is evidenced from intercropping in other crop systems. Intercropping is also one of the recommendations of the UNFCCC (United Nations Framework Convention on Climate Change) for the agriculture sector for climate change mitigation and adaptation. Depending on the type of intercrop used, intercropping can also fix nitrogen to the soil and also aid in carbon sequestration besides improving the soil water retention capacity and organic content. Hence, the intercropping of legumes with rice under SRI can be a good starting point in the direction of the transition of rice farming from the conventional industrial farming to agroecological farming [351].

# 3. MATERIALS AND METHODS

## 3.1. Research Methodology

The experiments were conducted at two levels—lab experiments at greenhouse chamber level and farmer-participatory experiments at field level. The greenhouse experiments were conducted in three batches of 5-7 months each in August 2017 -January 2018 (GH2017), February-June 2018 (GH2018a), and August 2018-February 2019 (GH2018b). The field experiments were conducted in two batches, one each in the summer of 2017 (FW2017) and in the summers of 2019 and 2020 (FW2019, FW2020) in Ganderbal and Islamabad (Anantnag) districts of Indian-adminstered Kashmir (referred to herefore as Kashmir) region respectively. Furthermore, field studies were done in 2018 to identify the partners for the field work and to do a feasibility study of the proposed interventions.

## 3.2. Greenhouse Experiments

Experiments were first conducted at greenhouse level to establish the proof of concept. Once the proof of concept was established, the innovation was optimized with further experiments. The optimization took into consideration the timing and spacing of the plants in an intercropping system. The initial experiments were conducted in pots of 20 cm diameter whereas the later experiments were conducted in mini-plots of 60 by 50 cm size. Experiments were first conducted under controlled conditions in a greenhouse chamber. Three sets of greenhouse experiments, with each lasting 5-7 months. In the initial experiment, rice growth under System of Rice Intensification (SRI) was compared to the conventional flooded rice (CFR). In the second experiment, another treatment called System of Rice Intensification with Beans Intercropping (SRIBI) was introduced.

In the first batch of greenhouse experiments, each treatment was replicated thrice (Figure 20) while as in the second and third batches 6 and 12 replications respectively were done. The three treatments compared in the first batch were: (i) rice cultivation conditions corresponding to SRI (SRI), (ii) conditions corresponding to SRI with intercropping of a legume (SRI+I), and (iii) conditions corresponding to conventional flooded rice (CFR). In the CFR treatments, three seedlings were planted together compared to single seedlings per pot in (i) and (ii). The CFR treatment in the greenhouse experiments did not completely follow conventional rice cultivation in that two of the usual SRI practices were adopted in this treatment: (i) compost application for plant and soil nutrition, and (ii) wider spacing between plants.

*Figure 20. A photographic representation of the experimental setup for the first (L) and second experiment (R)*

The salient features of the three different treatments are presented in tabulated form in the following table (Table 4).

*Table 4. The different experimental parameters in the three treatments of the first batch of experiments*

| Treatment | SRI | SRI+I | Flooded Rice (FR) |
|---|---|---|---|
| *Transplantation* | At 7 days, singly | At 7 days, singly | At 20 days, 3 seedlings together |
| *Spacing* | One hill per pot | One hill per pot | One hill per pot |
| *Fertilizer* | Compost | Compost | Compost |
| *Aeration* | Aerated weekly until 2 months | Aerated weekly until 2 months | Not aerated |
| *Watering* | Not flooded | Not flooded | Flooded |
| *Intercropping* | No | Yes | No |

The third batch of greenhouse experiments was done in mini plots to optimise the intercropping pattern. The experimental schema for the third experiment is shown in Figure 21. In this experiment, SRI was compared with SRIBI under different parameters of time and space. The three intercropping treatments were as follows:

i. SRIBI – I9: Intercropped SRI with beans sown between the rice rows at 9 days after transplantation (DAT)
ii. SRIBI – I35: Intercropped SRI with beans sown between the rice rows at 35 days after transplantation (DAT)

iii. SRIBI – IS: Intercropped SRI with beans sown as a separate row at 9 days after transplantation (DAT)

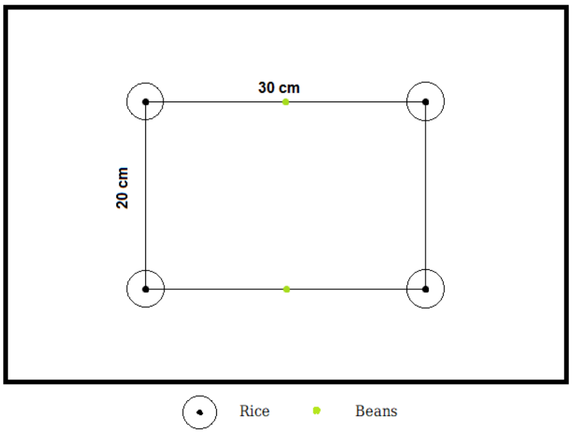



*Figure 21. A graphical representation of the intercropping setup in a mini-plot*

## 3.2. Field Experiments


*Figure 22. Location of the region, Kashmir valley (OpenStreetMap)*

The field experiments were conducted at two different places in the Kashmir valley region administered by India (Figure 22). The Kashmir region holds immense significance for the water security, and by extension, food security of both Pakistan and India. India and Pakistan being riparian states have a water sharing agreement called Indus Waters Treaty, which governs the use of the six rivers of the Indus System of Rivers. As per the treaty, for three of the six rivers, the western rivers—the Chenab, the Indus, the Jhelum—the control of the flow has been given to Pakistan while as the control of the 3 eastern rivers—the Beas, the Ravi, the Sutlej—has been given to India. Interestingly, all the three western rivers pass through the Kashmir region under Indian administration [352]. The major part of the rice ecosystem in Kashmir is fed from the waters of the river Jhelum (the Greek *Hydaspes*). Rice being the staple food in the Kashmir region and rice farming being a major source of livelihood in the region in addition to being the largest consumer of irrigation water, this research assumes significance in socio-economic, ecological, as well as political dimensions.


*Figure 23. Location of the two experimental sites in the Kashmir valley*

The design of field experiments followed the innovation process as detailed by Styger et al. (2011) in which the first year (2017, this case) involves a test experiment with a single plot to make the initial assessments about the applicability of SRI in the region [353]. In the second year (2018), the feasibility of scale up was examined in cooperation with local partners. In the third and fourth years (2019-2020), the intervention was scaled up with further innovation development.

The field experiments followed a Randomized Complete Block Design with four replications and a plot size of 60 m2 (10 m x 6 m) each. The experiments were carried out in two villages falling under the Sagam belt of Islamabad region (District Anantnag) in Kashmir, a popular niche belt of the local heritage aromatic landraces of Kashmir, particularly the Mushkibudij (Mushk Budji) variety used in the studies. The experimental fields are located at 33°36'31" N, 75°14'59" E and 33°36'54" N, 75°15'2" E, in Jammu and Kashmir (Figure 23). The elevation of the experimental site is at 1800 m amsl.

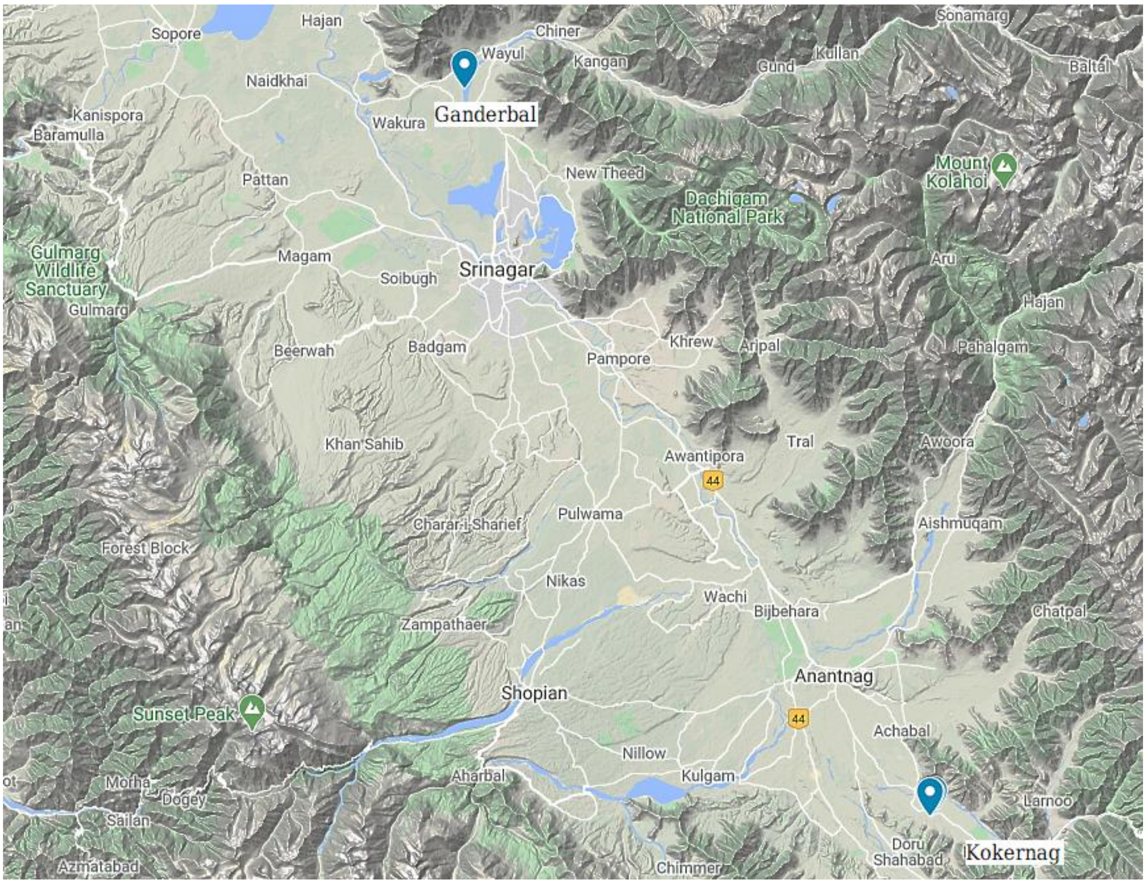



*Figure 24. A topographical representation of the two experimental sites, Ganderbal and Kokernag*

The first field experiment was carried out in April-September 2017, in Ganderbal, an area to the north of Srinagar, the capital of Kashmir, in cooperation with the Mool Sustainability Training and Research Centre. Ganderbal falls in the catchment area of the river Sind in Kashmir. Although some visible improvements in crop establishment in the initial stages after transplantation was observed, no significance difference in the yield was observed. The final round of field experiments were carried out in 2019 and 2020, in cooperation with Human Welfare Foundation (J&K) with the participation of a farmer's collective in the Kokernag area in Islamabad (Anantnag) district, to the south of Srinagar. Kokernag lies in the catchment area of the river Jhelum in Kashmir (Figure 24).

In these experiments, which together with the greenhouse experiments form the basis of our conclusions, 10 farmers took part in the studies, with a total experimental land area of 0.5 hectares. In 2019, the date of transplantation was the 19$^{th}$ of June, while as in 2020, it was the 10$^{th}$ of June. In the SRIBI (System of Rice Intensification with Beans Intercropping) treatments, legumes were introduced at 22 days after transplantation (DAT), which was midway between the 9 DAT and 35 DAT, the two treatments that were part of the greenhouse scale study.

### 3.2.1. Field Experiment Design

The field experiments with intercropping beans with rice under the System of Rice Intensification (SRI) management system involved the planting pattern as schematised in Figure 25. Rice was planted and managed following the standard SRI practices as described below.

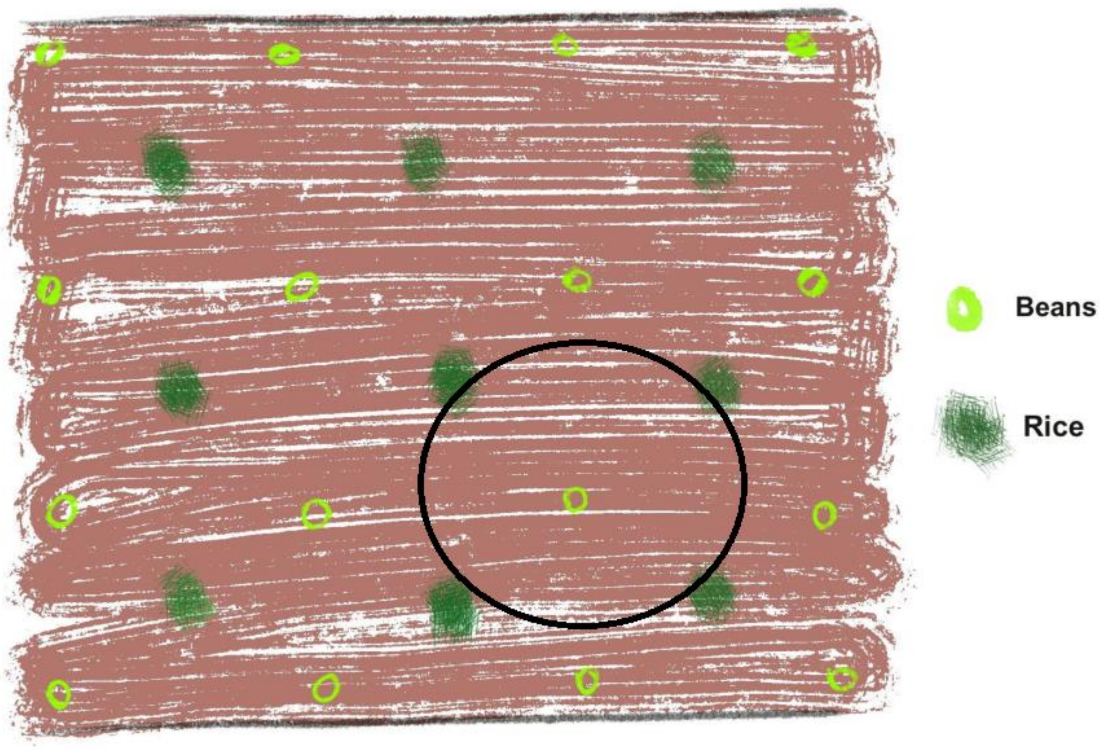



*Figure 25. A graphical representation of the rice and beans intercropping schema (CC BY-NC: Tavseef Mairaj Shah, Sumbal Tasawwar)*

The standard SRI practices that make it different from the conventional rice cultivation system are summarised as follows:

- *Watering the nursery to keep the soil just moist; no flooding of the field.*

- *Transplantation of the seedlings at the 2-leaf stage (10-14 day age).*

- *Transplanting single seedling per hill, with a wider spacing, in a square grid pattern (30 cm x 30 cm).*

- *Intermittent water application i.e. alternate wetting and drying of the rice field.*

- *Application of compost or organic fertilizers, preferably.*

- *Weeding with a rotary hoe/cono-weeder.*

In case of intercropping, the intercropping seeds (beans) are sown in the inter-crop row space after the first weeding done under SRI. The rough timeline that can be followed in this regard is shown in Figure 26.

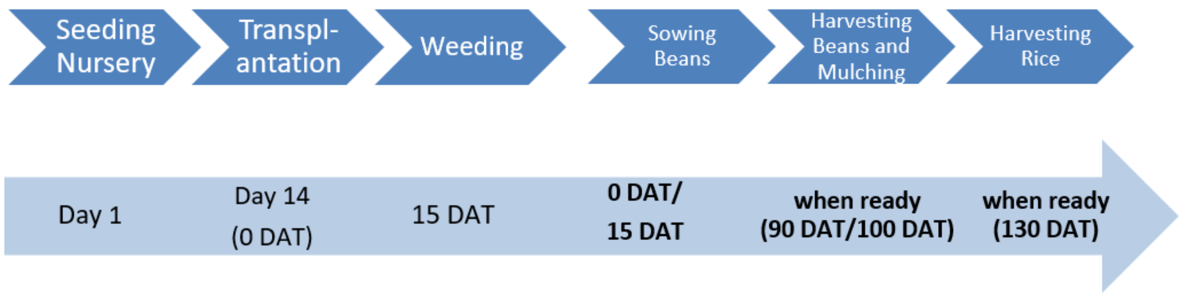



*Figure 26. A rough timeline that can be followed when intercropping rice with beans under the SRI management*

## 3.3. Materials and Conditions

### 3.3.1. Soil characteristics

The soil used in the greenhouse experiments was sandy clay loam soil (luvisol). The measured characteristics of the soil were: pH 7.3; EC 53.1 µS/cm; soil organic matter 1.10 %; total N 0.16 % ; total P 0.05%; total K 0.47 %. The soil was put into pots each 25 cm in diameter and 25.5 cm high, with 12 kg of soil in each pot. The soil organic matter content was found to be 11.25 % at the beginning of the GH2018b experiments.

The compost used had the following characteristics: total N 1.1%; total phosphate 0.45%; total potassium oxide 0.79%. Overall, 2.2 kg of compost was applied to each pot over the first 4 weeks after transplantation. This corresponds to per-pot application of: 24 g N; 9.8 g P; and 17.25 g K. The water applied to each pot was measured and documented.

### 3.3.2. Greenhouse conditions

The greenhouse conditions in which the experiments were conducted were with a temperature maximum of 28°C and humidity maximum of 75% (Figure 27). The photoperiod in the greenhouse was 13 hours.

**Temperature of the greenhouse**

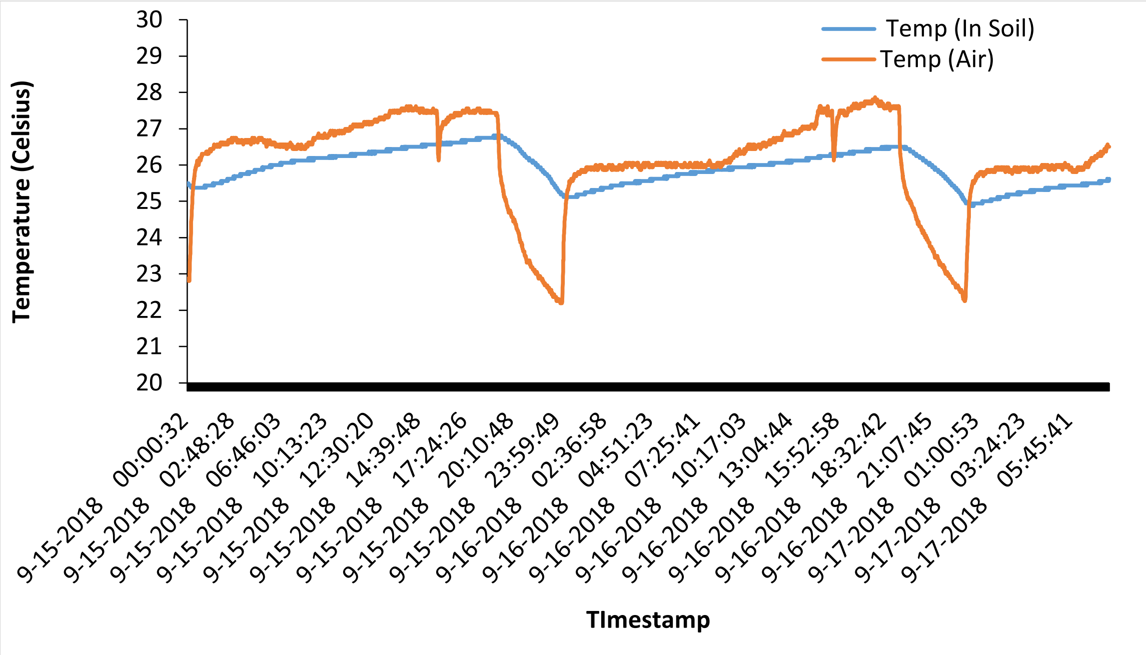



*Figure 27. Temperature variation in the greenhouse over a sample time period of 50 hours*

### 3.3.3. Seedling preparation

The rice variety used was Oryza sativa ssp. Japonica. The seeds were first allowed to germinate under warm and moist conditions and subsequently were sown in a tray nursery. The tray soil characteristics were as follows: pH 5.8; 120 mg/l N; 180 mg/l P; 700 mg/l K; and 95 mg/l Mg. The seedlings for SRI pots were transplanted at 7 days while as the ones for the flooded rice treatment were transplanted at 20 days age, which is somewhat earlier than the common rice cultivation practice of transplanting seedlings at about 5 weeks of age.

In the intercropped SRI pots (SRI+I) pots, bush beans (Phaseolus vulgaris) were directly sown into the pots after being soaked overnight, 2 seeds per pot, at 9 days after transplantation of the rice.

#### *3.3.3.1. Germination rate and seed vigor index*

The rice seeds were soaked overnight in water and then kept in a warm and moist environment (covered with layers of jute sacks that were kept moist) in order for them to germinate. The germination was observed after 60 hours. The seed quality and seedling growth was expressed in terms of germination rate, and the seed vigor index (SVI) was calculated using the following formula (Doni et al. 2017).

Seed Vigour Index (SVI) = Germination rate (%) x Seedling length (Shoot length + root length)

Germination rate (%) = 56 of 75 = 75 %

Here, germination rate refers to the percentage of the number of grains that germinated from the total number of grains that were put in.

Seedling length (@ 8 days) = (19.7+3.5) = 23.2 cm

SVI = 75 x 23.2 = 1740

## 3.4. Sampling & Analyses

The parameters that were measured or recorded in the greenhouse and field experiments are listed in Table 5.

*Table 5. List of parameters that were measured during the course of experiments*

| **Parameter** | **Greenhouse experiments** | **Field experiments** |
|---|---|---|
| *Chlorophyll content* | ✓ | |
| *Plant nutrient uptake* | ✓ | |
| *Soil organic matter* | ✓ | |
| *Water use* | ✓ | |
| *Number of leaves* | ✓ | |
| *Plant height* | ✓ | ✓ |
| *Number of tillers* | ✓ | ✓ |
| *Number of panicles* | ✓ | ✓ |
| *Panicle length* | ✓ | ✓ |
| *Spikelet number per panicle* | ✓ | ✓ |
| *Grain weight* | ✓ | ✓ |
| *Filled grains per panicle* | ✓ | ✓ |
| *Rice grain yield* | | ✓ |
| *Biomass/Straw/Fodder* | | ✓ |
| *Weed density* | | ✓ |
| *Labour requirement* | | ✓ |
| *Economic balance* | | ✓ |

### 3.4.1. Chlorophyll content

The chlorophyll content in leaves was measured at different growth stages—at the seedling stage and then at different days after transplantation. The method used for measurement was the same as used by Doni et al. (Doni et al. 2017), using the following formula:

$$C_{chl\text{-}a} = 12.7\,A663 - 2.69\,A645$$

$$C_{chl\text{-}b} = 22.9\,A645 - 4.68\,A663$$

Where A663 and A645 are the values of absorbance of the solution at wavelengths of 663 nm and 645 nm, respectively. The solution was prepared by cutting leaves into fine pieces and placing 0.1 g of the same into a test-tube to which 20 ml of 80% acetone was added. This solution was kept in the dark for 48 hours for incubation, and afterwards it was analysed with a spectrophotometer.

### 3.4.2. Plant growth characteristics

#### *Nutrient uptake*

Nutrient uptake in the plants was measured at the maturity stage (120 days). Rice plants were washed with water after harvesting and were allowed to dry, covered in paper bags, at 65 °C for 7 days. A mixture of all plant parts was then ground up to pass through a 1 mm sieve. This ground mixture was then analysed for NPK content. Nitrogen was measured by the Kjeldahl method, phosphorus by cuvette test (Hach Lange LCK350), and potassium by reflectometer method (Merck Reflectoquant RQflex 10 Reflectometer). Nitrogen content was also measured by a cuvette test (Hach Lange LCK138) and was found to be the same as the value determined using Kjeldahl method.

#### *Physiological characteristics*

The different plant physiological growth characteristics were recorded in mature rice plants (at 120 days). Plant height was measured as the length from the ground to the tip of the longest leaf. The number of leaves, number of tillers, number of panicles, and spikelets per panicle were measured by manual counting for each treatment. The plant fresh weight was measured by removing the plant from the soil, avoiding any significant damage to the roots. The biomass weight measurement was done after drying the plants at 65°C covered in paper bags for 7 days. In addition to this, the grain weight was also calculated at the maturity stage. The colour of the roots in different treatments was also observed.

**Statistical analysis.** The statistical analysis for ANOVA (Analysis of Variance) for data from field experiments was done using Statistix 10.0 (Trial version) analytical software (Tallahassee, FL, USA, https://www.statistix.com/). The statistical significance level in ANOVA was set at $p \leq 0.5$.

# 4. RESULTS AND DISCUSSIONS

## 4.1. Field Experiments – SRI (2017)

The first set of field experiments was conducted in May-September 2017. This set of experiments was meant to establish liaison with the farmers and to find the best way of practice to be utilized in the later experiments.

*Figure 28. (L) A view of the rice seedlings in the dry rice (SRI) nursery. (R) Rice seedlings transplanted singly in SRI pattern.*

In this set of experiments farmers were trained with the basic practices of the System of Rice Intensification (SRI) by demonstration in a trial field. The newly introduced SRI practices included setting up of a dry rice nursery, transplantation of the seedlings at the two-leaf stage, transplanting rice seedlings singly with a wider spacing, and the alternate wetting and drying of the field (Figure 28). Only a single plant growth parameter was recorded at the end of the experiment, which was the number of tillers that had grown from a single transplanted seedling. As seen in Figure 25, at 3 weeks after transplantation, the rice seedlings had grown and tillering had started by this time. At the time of harvest, the average number of tillers was found to be 14, which was higher than the number of tillers formed with conventional planting system (Figure 29).

*Figure 29. Rice plants at 3 weeks after transplantation. (R) Number of tillers from the stump of the rice plant after harvesting.*

## 4.2. Greenhouse Experiments – SRI and SRIBI (2017-2018-2019)

Experiments were conducted on greenhouse scale in four periods of 5-6 months each between August 2017 and April 2019 but the results of only three experiments were usable as one of them experiment had to be aborted midway due to crop failure in the greenhouse due to unconfirmable reasons (Figure 30). The results of the experiments mainly concern water use, nutrient uptake, chlorophyll content and different plant growth characteristics, which are summarised under the following headings.

*Figure 30. A photographic representation of the second batch of greenhouse experiments (GH2018a)*

### 4.2.1 Water use

The quantity of water used in SRI and SRI+I was considerably less than that used in FR. In GH2017 the water saving with SRI and SRI+I was 27%, a significant saving in a water-constrained world (Figure 31). In 2018a, the water savings in case of SRI and SRIBI was observed to be 39% when compared to the water needed for the CFR treatment. The fact that in case of larger pots (2018a), the water savings was higher possibly hints at a higher water saving potential with SRI with larger plots.  It was further observed that in the flowering stage, when the rice crop needs water, the soil in the SRI and SRI+I pots soaked up water easily, whereas in the flooded rice (FR) pots, the soil did not absorb water easily and the water remained standing on the surface for. This indicates that the soil is more porous under SRI management, probably indicating further greater presence and activity of the soil biota, with a higher water retention capacity. This also hints at the possibility that in case of flooding due to incessant rains, the SRI soil will hold more water and hence can prevent flooding or at least diminish it to a certain extent. These findings are in resonance with the findings of previous findings on water savings with SRI [27,28,354–356].

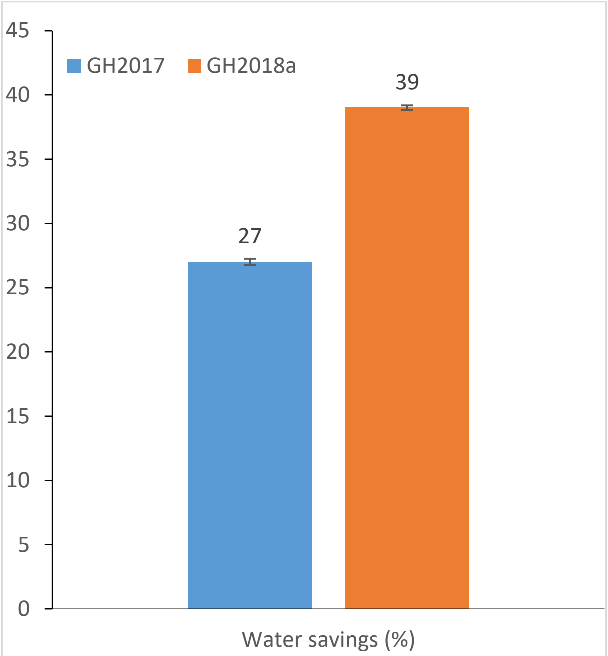



*Figure 31. Average water savings in SRI as compared to plants under conventional flooded treatment*

### 4.2.2. Nutrient uptake in the plants

In this study, the general effect on nutrient uptake found was that intercropping had a positive effect on the nutrient uptake in the rice plants cultivated with SRI methods.

*Nitrogen*

The nitrogen content in the mature leaves was found to be higher in SRI+I plants, indicating a higher nitrogen uptake. The nitrogen content was found to be 0.69% in SRI+I leaves, 0.64% in SRI leaves, and 0.58% in FR leaves (Figure 32). This can be attributed to the effects of nitrogen-fixing legumes intercropped with the rice on the soil, which include increased mycorrhiza formation and colonization [357]. A higher N-uptake is a sign of better growth of plants and a higher yield potential. The higher nitrogen uptake, and nutrient uptake in general, in case of SRI has also been attributed to the greater biomass and vigour of roots under SRI management [358,359]. The differences in nitrogen uptake were consistent across all replications of the three treatments and significant ($P < 0.05$). Among the different intercropping treatments, the highest nitrogen uptake was recorded in the strip intercropping treatment (IS) (Figure 33).

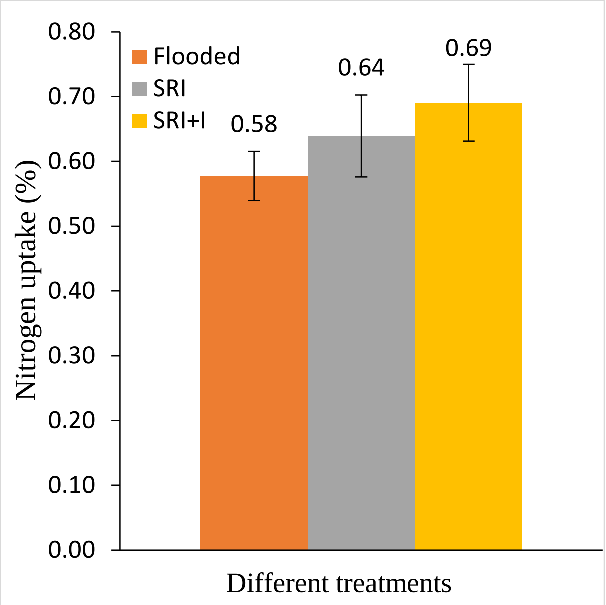



*Figure 32. Nutrient uptake in flooded rice, SRI, and SRI with intercropping in the first experiment (2017 GH)*

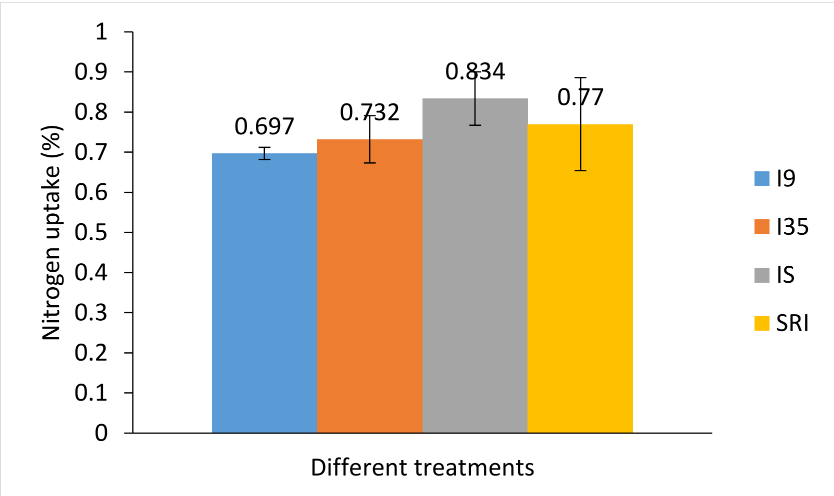



*Figure 33. Nutrient uptake in SRI and different configurations of SRI with intercropping in the third experiment (2018b GH); I9: intercropping at 9 DAT; I35: intercropping at 35 DAT; IS: intercropping as strip cropping at 9 DAT*

### Potassium

The potassium content in SRI+I rice plants was also recorded to be higher than in the SRI plants, indicating a higher phosphorus uptake in the rice intercropped with beans, although not higher than with FR treatment. The potassium content was found to be 2.75% in SRI+I leaves, 2.43% in SRI leaves, and 2.80% in FR leaves (Figure 34). In this case as well, the trend was similar across the three replications, with SRI+I recording higher phosphorus-uptake than unmodified SRI ($p < 0.05$) although there was no significant difference from FR practice. The slightly higher uptake of potassium in flooded rice observed in this study follows the trend observed by Beyrouty et al. (1994), who also observed that potassium uptake did not limit growth when compared between flooded and intermittent irrigation [360]. Among the different intercropping treatments, the highest potassium uptake was recorded in the intercropping at 9 DAT treatment (I9) (Figure 35).

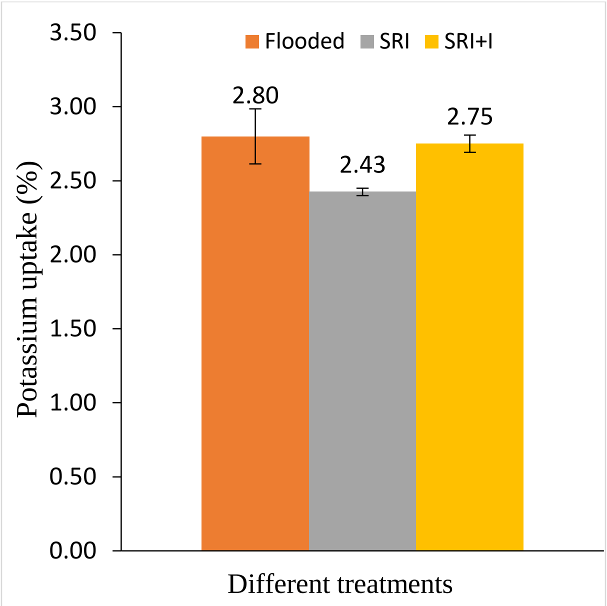



*Figure 34. Nutrient uptake in flooded rice, SRI, and SRI with intercropping in the first experiment (2017 GH)*

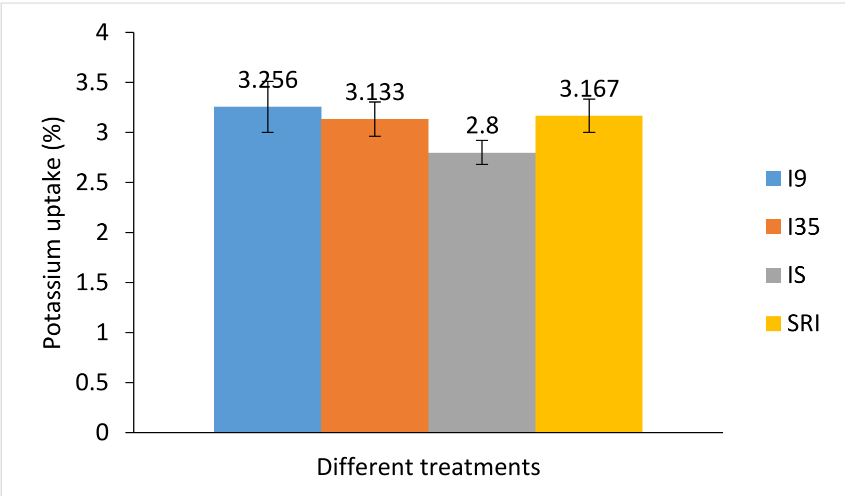



*Figure 35. Nutrient uptake in SRI and different configurations of SRI with intercropping in the third experiment (2018b GH); I9: intercropping at 9 DAT; I35: intercropping at 35 DAT; IS: intercropping as strip cropping at 9 DAT*

### *Phosphorus*

The phosphorus uptake in SRI+I was also higher than with the other two treatments, seen from the significantly higher phosphorus concentration in mature leaves. The phosphorus content was found to be 0.33% in SRI+I leaves, 0.25% in SRI leaves, and 0.22% in FR leaves (Figure 36). The phosphorus uptake was significantly higher in SRI+I treatment than in the other two treatments ($P < 0.05$). The higher uptake of Phosphorous in SRI and SRI+I can be attributed to vigorous and early root establishment as pointed out by Jogi et al. [361]. Phosphorous acquisition has been described as a limiting factor in plant growth and phosphorous is an important micronutrient for plants [362–364]. Among the different intercropping treatments, the highest nitrogen uptake was recorded in the intercropping at 9 DAT treatment (IS) (Figure 37).

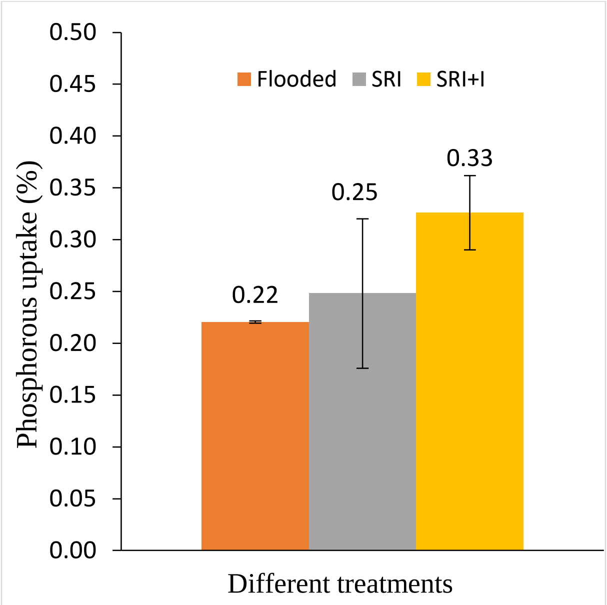



*Figure 36. Nutrient uptake in flooded rice, SRI, and SRI with intercropping in the first experiment (2017 GH)*

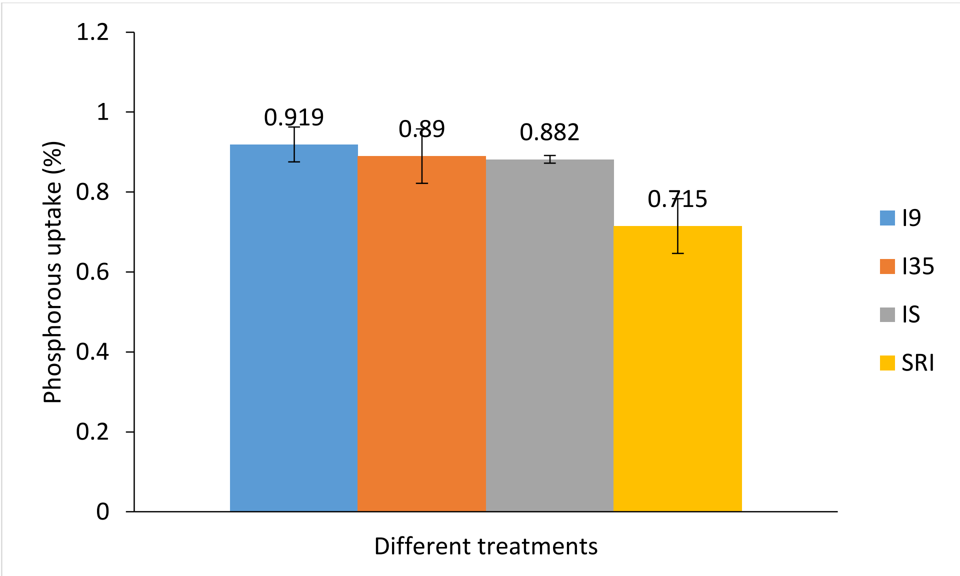



*Figure 37. Nutrient uptake in SRI and different configurations of SRI with intercropping in the third experiment (2018b GH); I9: intercropping at 9 DAT; I35: intercropping at 35 DAT; IS: intercropping as strip cropping at 9 DAT*

The individual values of nitrogen, phosphorus and potassium uptake in the case of SRI+I were significantly higher than in SRI ($P < 0.05$). The contribution of legume intercropping to the NPK nutrient uptake in upland rice plants can be attributed to the nodule-forming ability of the legume plants as well as to vesicular-arbuscular mycorrhizae [365]. It has been reported that in cereal and legume intercropping, mycorrhizae formation is increased, leading to improved nodulation and hence to increased acquisition of N and P [357].

*Soil Organic Matter*

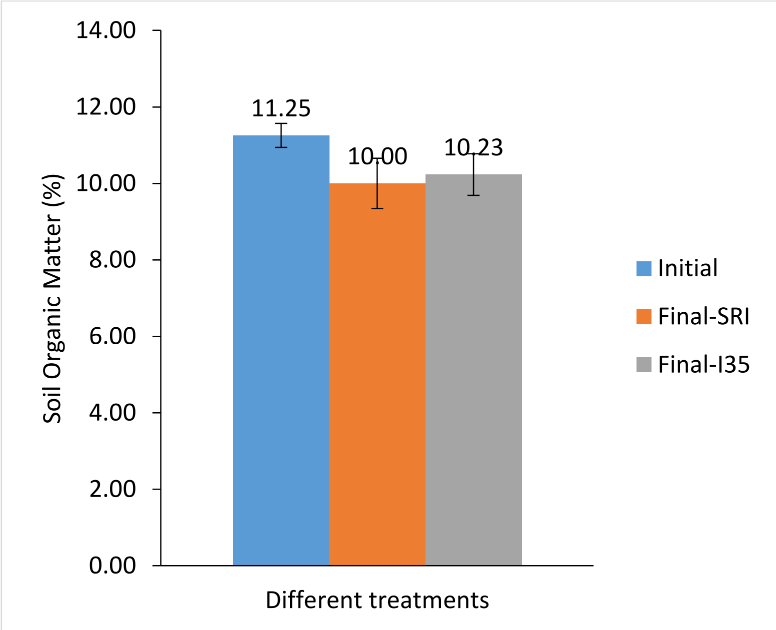



*Figure 38. A comparison of the final organic matter in soil in SRI and intercropping pots (GH 2018b)*

The soil organic matter content was also measured at the end of experiments in GH 2018b batch. The organic content was found to be slightly higher in case of intercropped SRI than in SRI, as shown in Figure 38. Any improvements in the organic content of soil can lead to improvement in different plant growth supporting characteristics of the soil [366,367].

### 4.2.3. Chlorophyll content

The content of both chlorophyll-a and chlorophyll-b was considerably higher in SRI+I leaves than in the leaves of either SRI or FR. The measured chlorophyll-a and chlorophyll-b contents were 12.85 and 3.87 µg/g; 9.15 and 2.83 µg/g; 9.34 and 3.03 µg/g for SRI+I, SRI and FR treatments, respectively (Figure 39 and Figure 40).

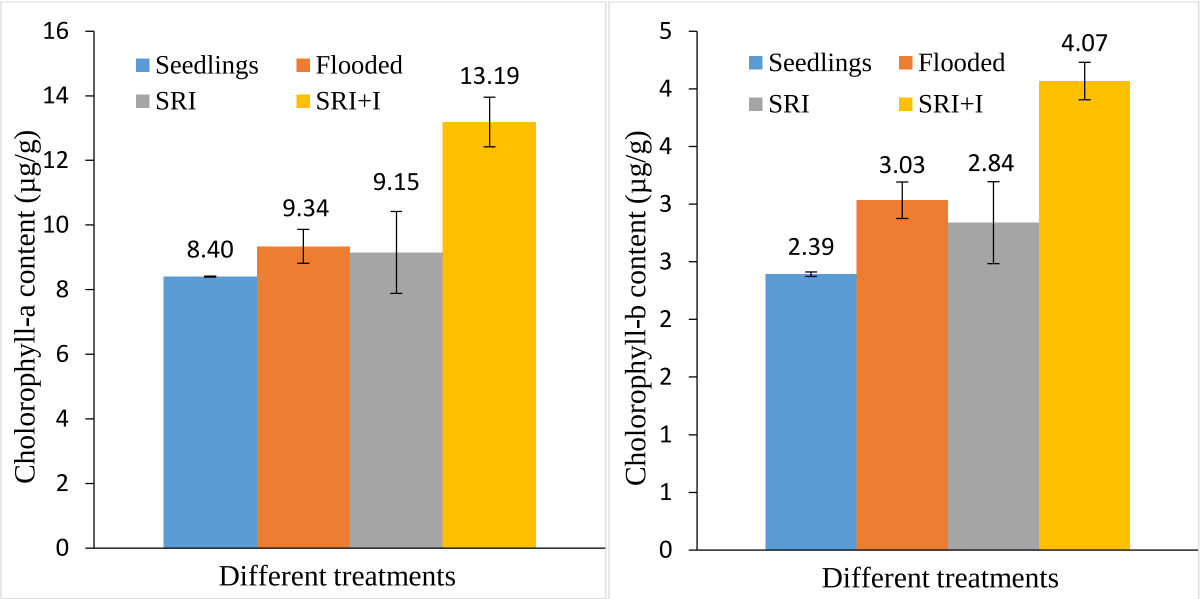



*Figure 39. A comparison of the chlorophyll content (a and b) in the leaves in the first experiment (GH 2017)*

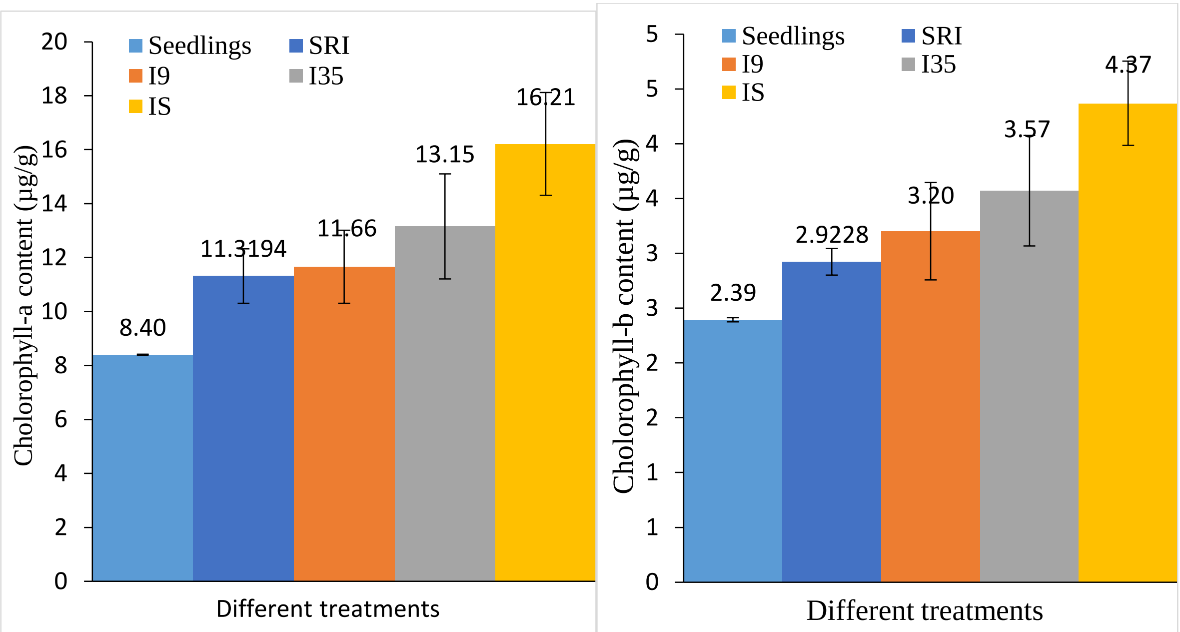



*Figure 40. A comparison of the chlorophyll content (a and b) in the leaves in the third experiment, featuring different intercropping configurations (2018b)*

It can be seen from the data that intercropping had a strong positive impact on the chlorophyll content of the rice plant leaves under SRI. The observed data suggests that SRI and intercropping improve the chlorophyll content of the leaves. Chlorophyll content in crops has been suggested to be linked to increase biomass production and grain yield in the crops [368]. Based on these numbers, it can be expected that intercropping leads to an improved performance of the rice crop.

### 4.2.4. Plant physical characteristics

All of the following parameters were measured at 120 days after transplantation. Generally, the plant growth characteristics were found to be better for all SRI configurations as compared to flooded rice. In case of SRI intercropped with legumes, the plant growth parameters were found to be better than normal SRI. These findings are in line with other comparative studies on SRI and flooded rice reporting better growth parameters in rice under SRI management [369,370]. These improvements indicate that an alternative to the current input-intensive, agrochemicals-driven, and market-dependent farming system under the auspices of agroecological farming is possible, which has the potential to improve the current food system.

*Number of leaves*

The number of leaves was found to be the highest in case of SRI+I with an mean of 58 followed by SRI at 41 and FR at 39.

*Plant height*

The plant height was measured as the length of the tallest leaf observed. SRI plants recorded the maximum height with 103 cm, with SRI+I and FR at 92.5 and 94.5 cm, respectively in GH2017. The average height observed in the rice plants for the four different treatments followed an increasing trend in the order: IS < I9 < SRI < I35. The four treatments recorded average values of height as 87.67, 91.33, 94.00, and 96.33 in that order, in GH2018. The highest plant height observed for each treatment is shown in Figure 42.

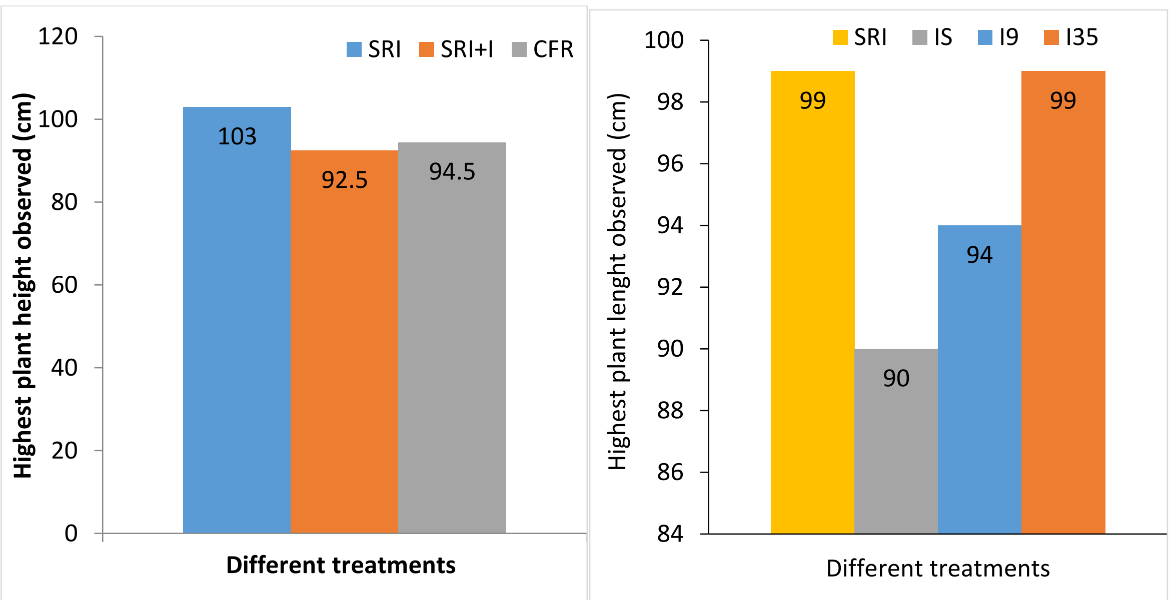



*Figure 41. Highest plant height observed in the different intercropping treatments compared to SRI (GH2018b)*

*Number of tillers*

*Table 6. A comparison of the number of tillers in flooded rice, SRI, and intercropped SRI at three different stages of growth in the GH2017 batch*

| Age (DAT) | SRI+I | SRI | FR |
|---|---|---|---|
| *28* | 5-8 | 2-3 | - |
| *65* | 8 | 5 | 6 |
| *120* | 22 | 12 | 10 |

Tiller number set the SRI+I treatment distinctly apart from the other two treatments. The number of tillers per pot at the time of harvest was 22 in SRI+I, while as it was 12 and 10 for SRI and FR, respectively (Figure 43-44). The higher number of tillers per plant in SRI+I was visible in the early stages of the plants themselves. At 28 days after transplantation (DAT), the number of tillers in SRI+I was 5-8 across the three replications, while as it was 2-3 in the case of simple SRI. At the age of 65 days after transplanting, SRI+I had 8 tillers while as SRI had 5 tillers. At around the same age, the FR plants had 6-10 tillers per pot (Table 6).

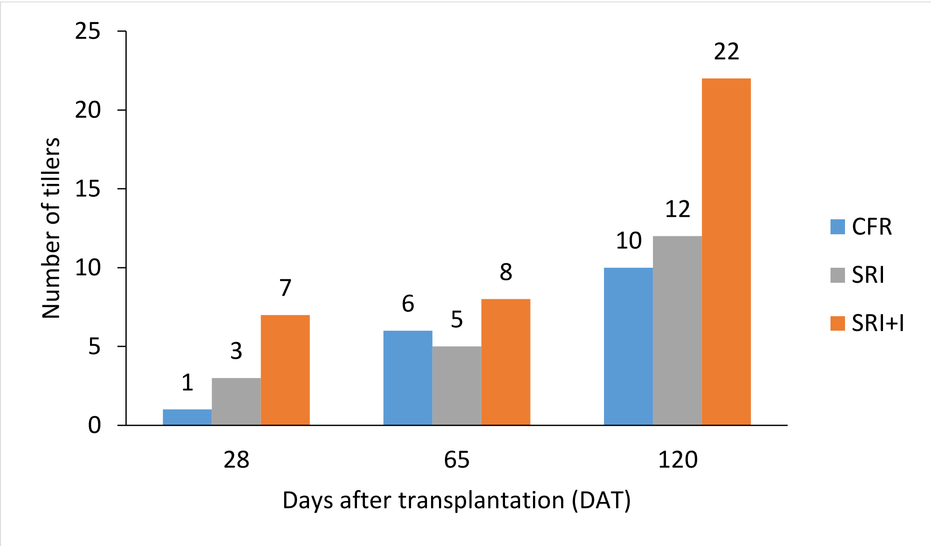



*Figure 42. Graphical representation of the number of tillers in flooded rice, SRI, and intercropping treatments*

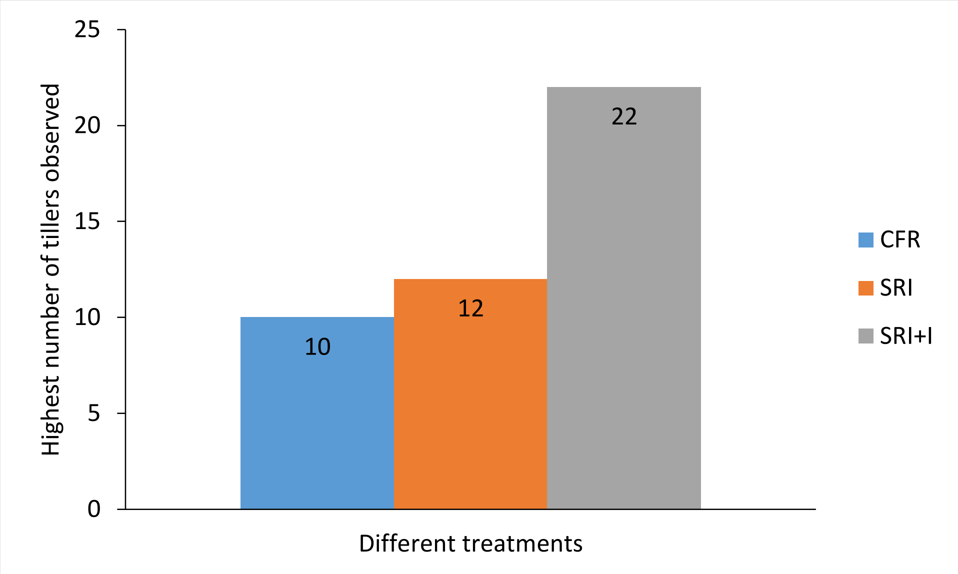



*Figure 43. Highest number of tillers observed in the three treatments in the first experiment (GH2017)*

In terms of the different time-based intercropping configurations, I-35 (intercrop sown at 35 DAT) was observed to have more number of tillers than I-9 (intercrop sown at 9 DAT). The number of tillers in I-9 were not very different from that in SRI, as can be seen in Figures 45 and 46. This could also hint at the possibility that intercropping at 9 DAT was too early to show any improvements in the plant growth characteristics.

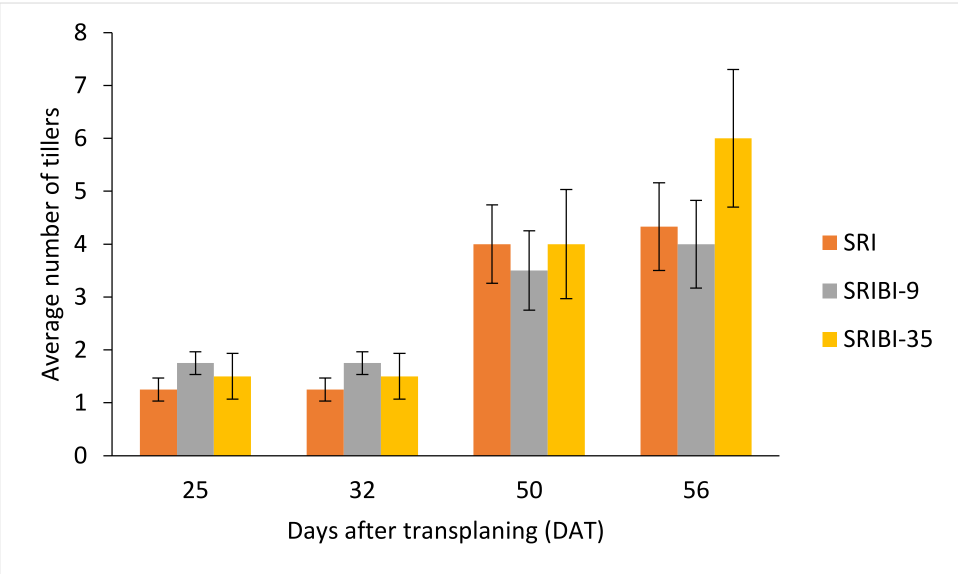



*Figure 44. Number of tillers in SRI and two different intercropping treatments (GH2018a)*

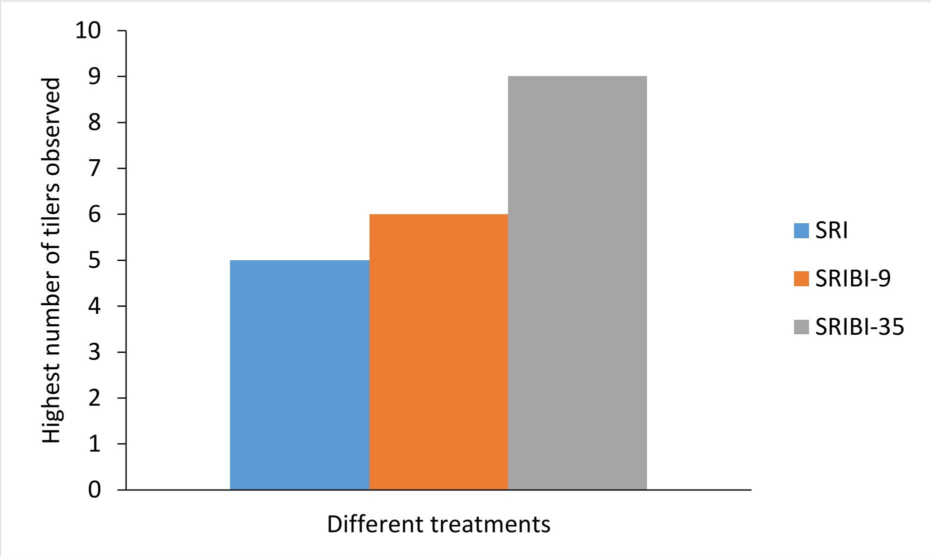



*Figure 45. Highest number of tillers observed in SRI and two different intercropping treatments (GH2018a)*

In terms of space-based differences in the different intercropping configurations, a higher number of tillers was observed in strip cropping (IS) as compared to I-9 and I-35 (Figure 47-48). Although strip intercropping (IS) showed a higher number of tillers compared to the other two intercropping configurations (I9 and I35), it was not the better one in terms of yield. This was because panicle initiation was observed the latest in the IS configuration. Hence it was I9 and I35 that were marked as the potential configurations for field experiments.

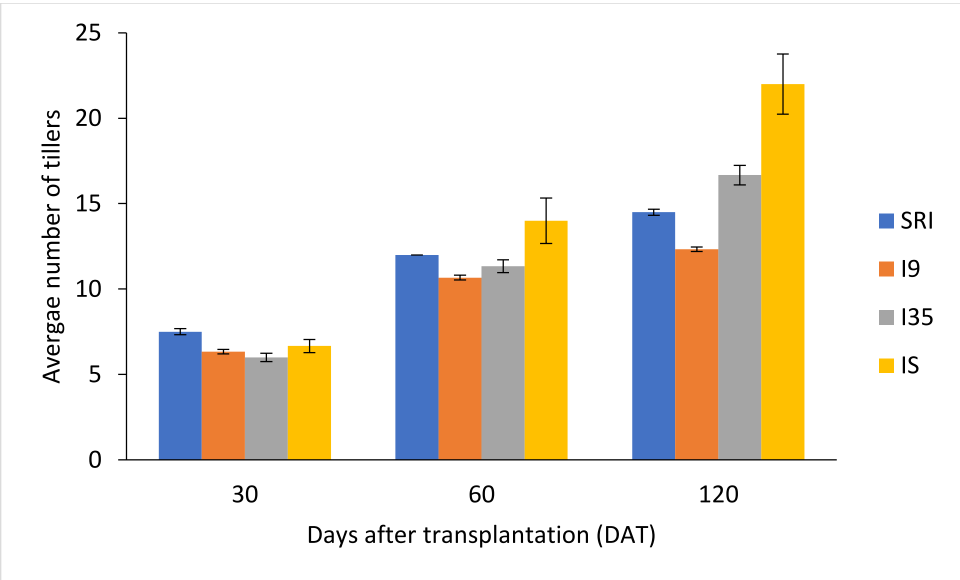



*Figure 46. Number of tillers observed in different intercropping configurations in GH2018b at different stages of growth (GH2018b)*

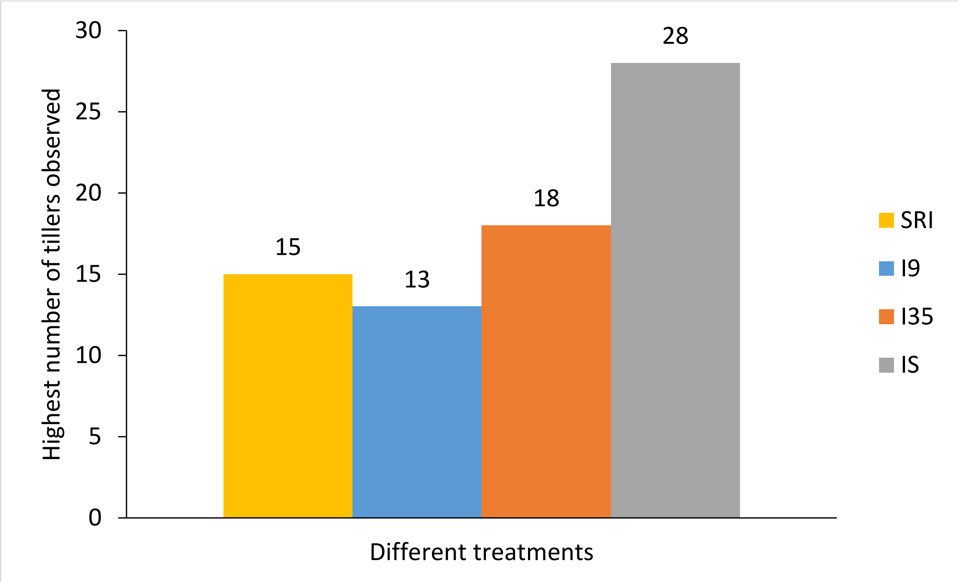



*Figure 47. Highest number of tillers observed in the different intercropping configurations compared to that of SRI (GH2018b)*

It can be inferred from the number of tillers at different stages that the SRI+I treatment led to a higher number of tillers in the vegetative phase, which is important for the productivity of the plant. However it was also seen that the number of tillers kept on increasing well into the reproductive phase in some replications of the SRI+I treatment. As a result, SRI+I plants took more time to mature compared to the other two treatments. This effect was however not observed in the field experiments, where in some cases plants under intercropping matured faster. However, the effect of this later tillering on the yield parameters is discussed below.

*Panicle characteristics*

The number of panicles per pot was also distinctively higher with SRI+I than with the other two treatments, i.e., 20, compared to 11 and 9 for SRI and FR, respectively. The number of grains per ripe panicle was 143, 103, and 118 for SRI, SRI+I, and FR, respectively. The panicle length was 22 cm, 14 cm, and 19 cm for SRI, SRI+I, and FR, respectively, which shows a positive correlation with the number of grains per panicle. The spikelets per panicle were lesser in the case of SRI+I than for both of the other treatments. For SRI, it was 120, while as for SRI+I and FR it was 60 and 80, respectively.

*Maturity percentage*

As a result of the above mentioned phenomenon, the average percentage of ripened panicles at the time of harvest (120 days after transplantation) in the case of SRI+I was very low, 30%, while as it comparatively higher for SRI, 40%. The percentage maturity of panicles was highest in case of the FR treatment, around 70%. However, since the total number of panicles was higher for SRI+I and SRI treatments, the number of ripened panicles was the same for CFR and SR+I treatments, 6, while as it was 5 for SRI. The lower maturity of panicles, or lower filled spikelet percentage in rice has been attributed to a higher availability (input) of nitrogen371. In the field experiments, however, the ripening was not delayed and SRI+I had better yield characteristics.

*Yield*

The yield of SRI+I in these trials was the same as for SRI and considerably less than for FR. The total ripened grain weight per pot was 12 g, 11 g, and 22 g per pot for SRI+I, SRI, and FR, respectively. The mean individual grain weight for the three treatments was, however, in the same range: 23.6 mg, 24.1 mg, and 25 mg for SRI, SRI+I, and CFR, respectively.

The fact that there was no difference in the per grain weight despite there being large differences in the per-pot grain yield further suggests that the lag in ripening was a major factor in determining the differences in yield. Although FR had a lesser number of panicles than SRI and SRI+I, a higher filling-efficiency led to higher yield of FR in this study. The SRI and SRI+I results were characterized by more unfilled grains and unripe panicles despite having significantly higher number of tillers and panicles. If the SRI+I pots had been harvested at maturity and their yield weighed then, their production would have been considerably more.

*Figure 48. Beans intercropped with rice under SRI*

The 1000-grain weight was in the range of 20-24 g for all three treatments. However, in the case of SRI+I, there is also the 2 g of beans per pot (2 pods per plant) that were harvested, with a pod fresh weight of 6 g to be considered (Figure 49).

*Plant biomass weight*

There was no difference observed in shoot biomass per pot, which was 31 g, 30 g, and 30 g for SRI, SRI+I, and FR, respectively. The root biomass was 7 g, 5 g, and 5.5 g for SRI, SRI+I, and FR, respectively. It was observed that roots in case of SRI and SRI+I were vigorous and better distributed radially, whereas the roots in the FR treatment were feeble and localized axially at the time of harvest. The root colour was observed to be mostly dark brown to black for the FR plants, and light brown to white for the SRI and SRI+I plants, which is indicative of better health of roots for the latter (Figure 50). The health of the root system is indicative of the growth potential of the crop [371,372].

Figure 49. A comparison of the root system for SRI, SRI+I, and Flooded Rice plants (L-R)

*Spikelets and panicles*

The average panicle length was observed to be the generally higher in case of intercropping treatments. The average panicle length observed was 14.67, 15.83, 12.00, and 14.50 cm for I9, I35, IS, and SRI respectively. The highest panicle length recorded was observed in the case of I35, which was 20 cm (Figure 51).

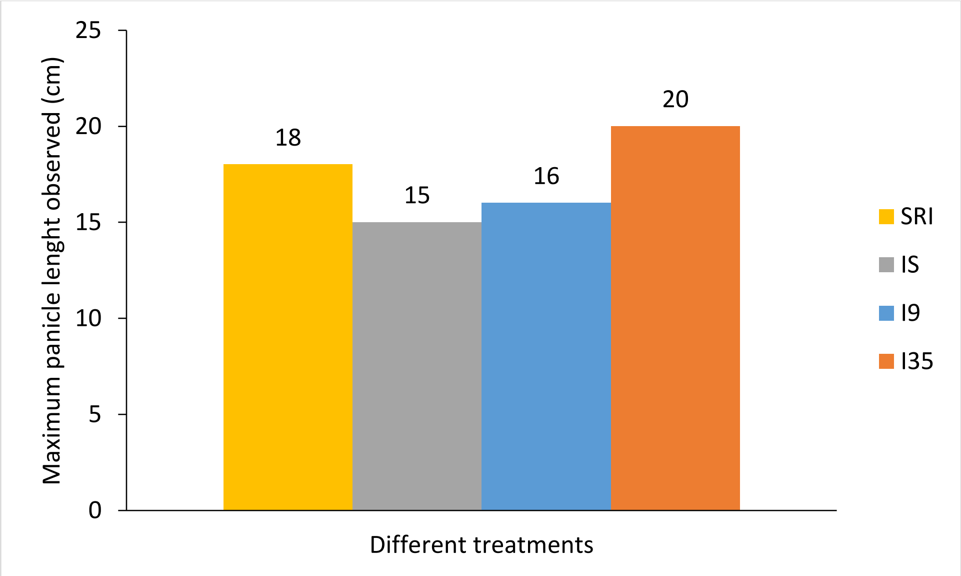



Figure 50. Panicle length maximum in the different intercropping treatments compared to SRI (GH2018b)

*Yield*

The average number of spikelets per panicle followed a trend similar to the panicle length, with I9, I35, IS, and SRI recording 122.64, 109.36, 80.00, and 96.00 respectively (Figure 52).

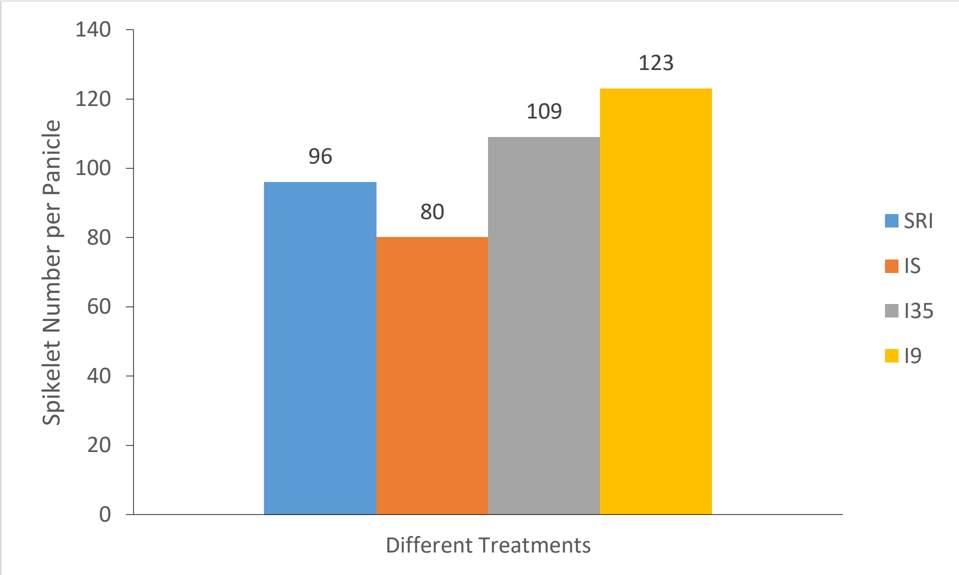



*Figure 51. Spikelet Number per Panicle (GH2018b)*

The average 1000 grain weight was found to follow a similar trend, with two of the intercropping treatments recording a higher average than SRI. The observed values were 18.67, 25.00, 20.33, and 20.50 grams per 1000 grains for I9, I35, IS, and SRI respectively. I35 and IS both recorded a high of 27 grams respectively (Figure 53).

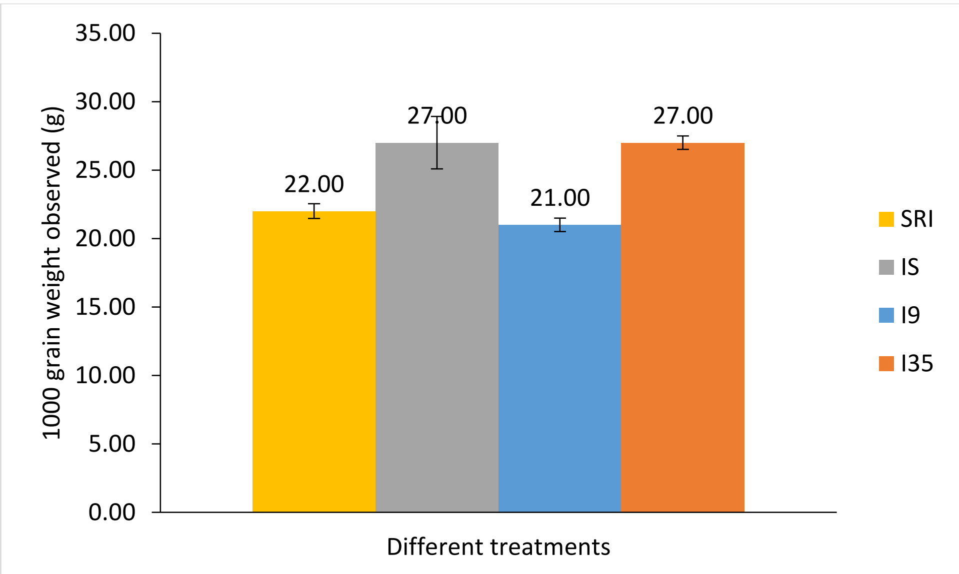



*Figure 52. The yield parameter of 1000 grain weight for the different treatments (GH2018b)*

In conclusion, it was the treatment I35 that was found to be the best in terms of different plant growth characteristics. However, the I9 treatment was observed to be better than I35 in certain characteristics e.g. the spikelet number per panicle (SNPP).

## 4.3. Field Studies (2018)

Field studies were conducted in the summer of 2018 to identify feasible areas and partners to scale up the experiments conducted in the previous year (Figure 54). In this regard field trips were conducted to examine the current condition of rice farming in the region and to assess the challenges faced by the farmers with respect to rice cultivation. In Kashmir, generally the water availability for crop cultivation has been dwindling over the years. This has made rice farming more difficult and laborious in the recent past, leading to some farmers giving up rice cultivation for good.

*Figure 53. Rice fields being prepared for transplantation under flooded conditions (April-May 2018)*

In 2018, on March 26, the Irrigation and Flood Control department in Kashmir issued an advisory asking farmers not to grow rice that year due to low availability of water [373–375]. This was a result of low precipitation in the late winter that year (Figure 55). However, in order to inform the farming fraternity about alternative ways of cultivating rice, I wrote an article for the most widely circulated English newspaper in Kashmir detailing the System of Rice Intensification [376]. This also set into motion discussions around SRI in the agricultural circles in Kashmir leading to the local agricultural university (SKUAST-K) promoting SRI as an alternative in water scarce conditions [377]. Even though the availability of irrigation water was scarce, farmers still reported good yields, dispelling the fears that rice cannot grow under water scarce conditions [378].

*Figure 54. Dried up rice fields due to non-availability of irrigation water (June-July 2018)*

With respect to general farming practices, it was observed during the field studies that intercropping of legumes is already widely in practice in crops such as maize and wheat, which are grown in dry conditions (Figure 56).

*Figure 55. Intercropping of beans with maize.*

## 4.4. Field Experiments – SRIBI (2019-2020)

The results of the field experiments in 2019 and 2020 strongly evidenced the proof of concept established from the results of the preceding greenhouse experiments of the previous years. Most of the physical growth characteristics of the rice plants measured during the study showed marked improvements in the rice plots under SRI with beans intercropping (SRIBI) regime compared to plots under simple SRI. Although the flooded rice plots (CFR) were transplanted 2 weeks before the SRI and SRIBI, the parameters for SRIBI were still found to be better when compared at 110 days after transplantation (DAT). In case of SRI and SRIBI, weeds were allowed to be grown after the first weeding for comparison, as a result of which some parameters for SRI were expected to be weaker than CFR. The SRI treatment in the current study is also referred to as SRI-w (weedy control) interchangeably.

### 4.4.1. Plant physical characteristics

The effect of intercropping on the different rice plant growth characteristics observed in the field experiments is summarised in the following sections, visualised in the form of bar graphs. In general, an improvement in the plant growth characteristics was observed in case of SRI with Beans Intercropping (SRIBI) as compared to simple SRI. The overarching reason behind the improved growth parameters under intercropping can be attributed to the enhancement of nitrogen availability to the rice plants due to intercropping as nitrogen content is an important indicator of growth in crop plants [357,362,379,380] (Figure 57).

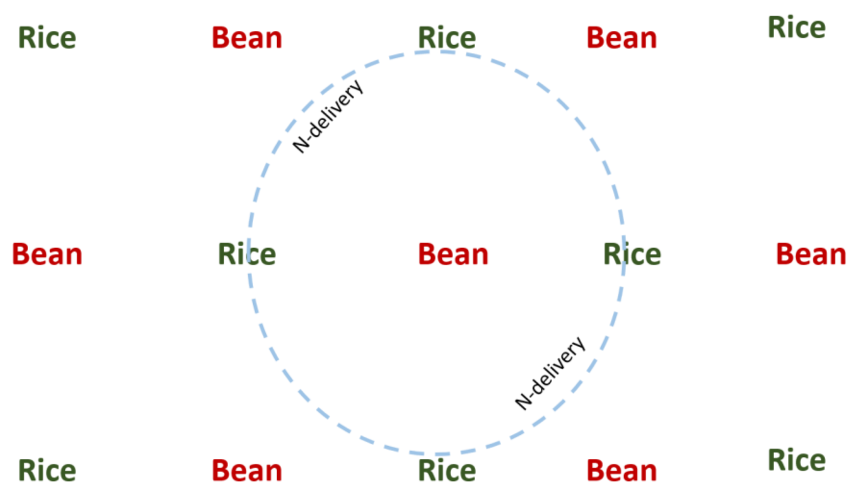



*Figure 56. A theoretical representation of enhanced nitrogen availability to the rice plants under intercropping regime (CC: Ralf Otterpohl)*

*Height*

In the 2019 experiments, the maximum height observed for CFR, SRI, and SRIBI was 136cm, 125 cm, and 148 cm respectively (Figure 58). While as the mean height observed for CFR, SRI, and SRIBI was 125 cm, 119 cm, and 123 cm respectively. The increase in height in case of SRIBI in comparison to SRI was found to be statistically significant ($p \leq 0.05$; p=0.05). In 2020, the advantage of SRIBI over SRI and CFR was again evidenced with the highest recorded height values for the three treatments being 101 cm, 104 cm, and 109 cm respectively.

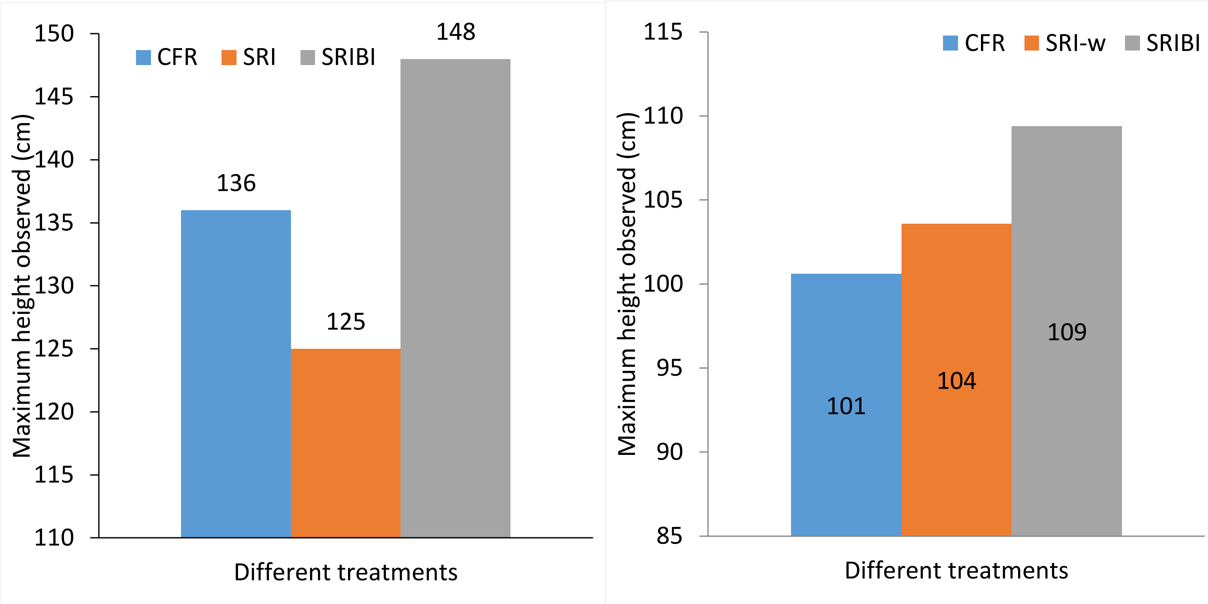



*Figure 57. A comparison of maximum plant height achieved in CFR, SRI and SRIBI regimes (Left: 2019; Right: 2020)*

When compared for two different legumes intercropped with rice under SRI, intercropping with Mong – mung beans (SRIBI-M) was found to show better plant growth than intercropping with Razma – kidney beans (SRIBI-R). The maximum height observed for SRI, SRIBI-R, and SRIBI-M was 124cm, 131 cm, and 139 cm respectively (Figure 59). While as the mean height observed for SRI, SRIBI-R, and SRIBI-M was 116 cm, 122 cm, and 126 cm respectively.

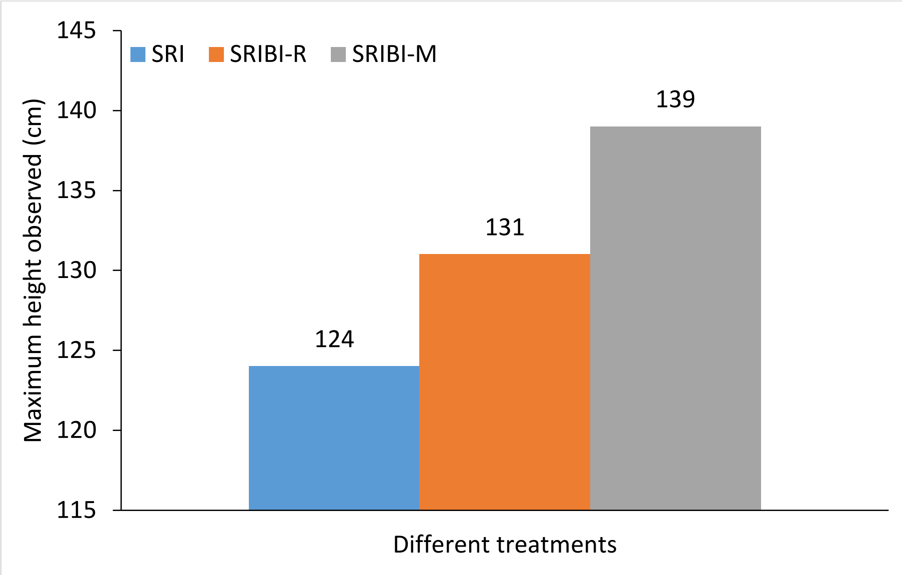



*Figure 58. A comparison of maximum height in SRI and two SRIBI regimes with different legumes*

*Number of tillers*

The effect of the SRI method on the tillering [381–383] was clearly visible in the studies. On an average, the SRI-based plots, including SRIBI, showed three times the number of tillers as compared to the conventional flooded rice (CFR). The average number of tillers in SRIBI and CFR was observed to be 26.33 and 9.50 respectively, while as the highest number of tillers observed was 39 and 14 respectively, in 2019 (Fig. 56). The difference in the number of tiller was found to be statistically significant ($p \leq 0.05$; p=0.0001). In 2020, the average number was 34, 30, and 12 for SRIBI, SRI, and CFR respectively (Figure 60).

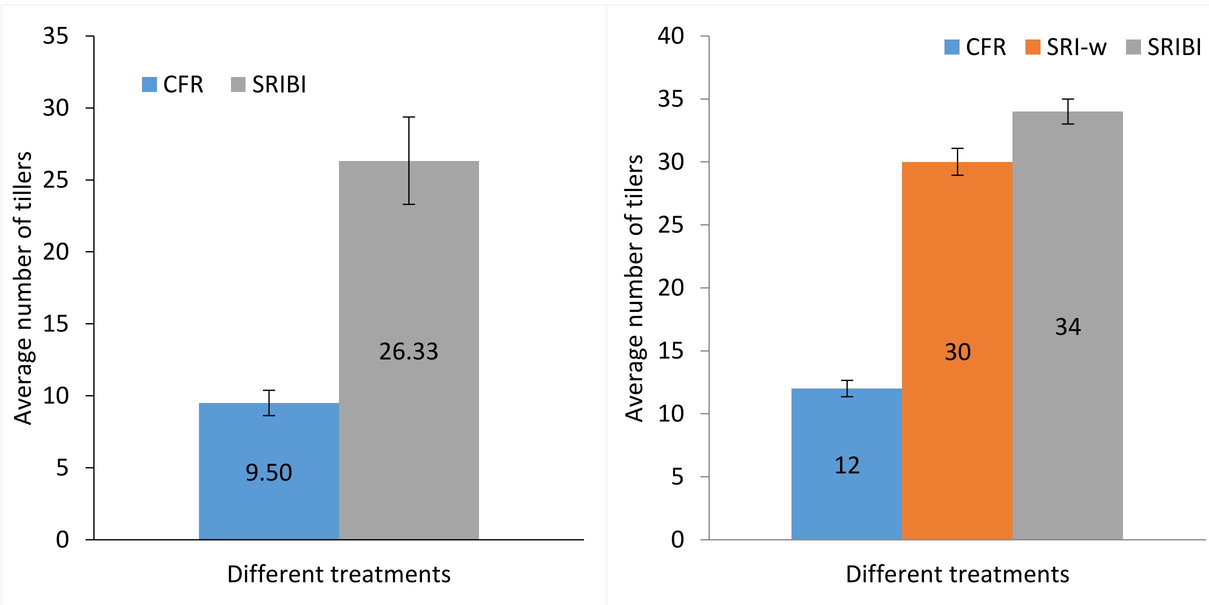



*Figure 59. A comparison of the number of tillers under CFR and SRI-based regimes (Left: 2019; Right: 2020)*

### 4.4.2. Yield characteristics

*Panicles length*

The panicle length has a minor correlation with the yield of the rice crop (Ramakrishnan et al., 2006; Bhutta et al., 2019), which could give an idea about the yield potential of a particular crop management system. In 2019, the mean panicle length from the sample size was 24 cm, 22 cm, and 22 cm for CFR, SRI, and SRIBI respectively. The difference among the three treatments was found to be statistically insignificant ($p > 0.05$; $p=0.065$). However, in 2020, the panicles of the SRIBI treatment were markedly longer than of SRI-w and CFR (Figure 61).

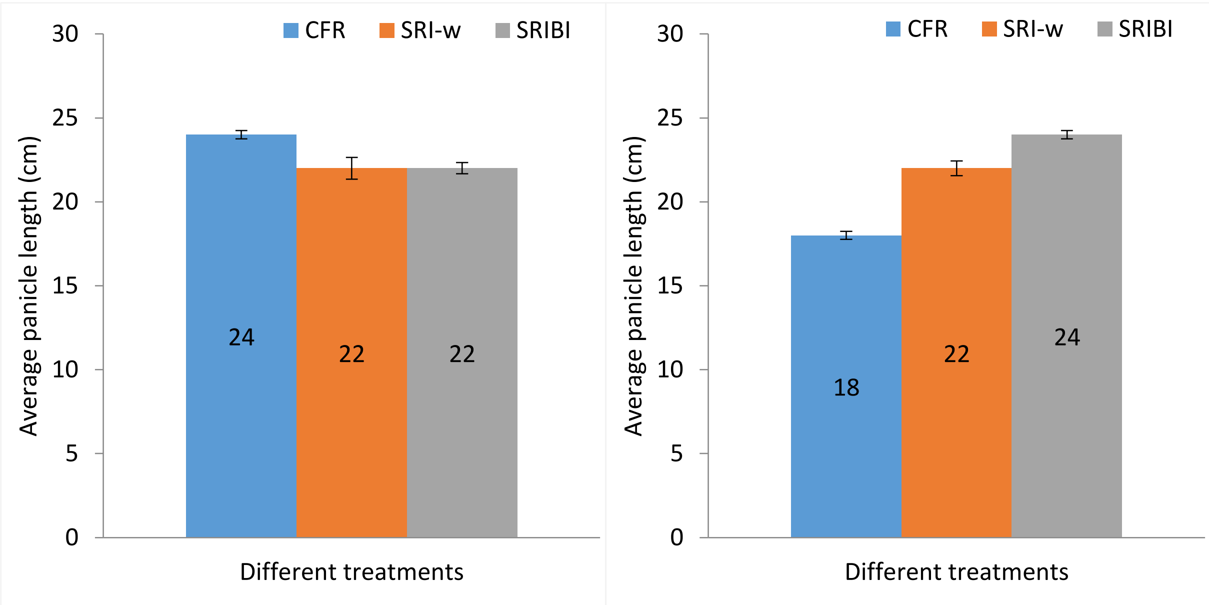



*Figure 60. A comparison of average panicle length in CFR, SRI, and SRIBI (Left: 2019; Right: 2020)*

*Yield*

Spikelet number per panicle (SNPP) is one of the most important yield components used to estimate rice yields (Zhao et al. 2015), and is linked with the number of grains. And, grains per panicle shows a significant positive correlation with yield [384,385], and with a higher number of spikelets per panicle, higher number of grains per panicle is expected. Given that the spikelet number per panicle was significantly higher ($p \leq 0.05$; $p=0.0001$) in case of SRIBI as compared to CFR and SRI, it can be deduced that the grain yield of rice can improve under intercropping regime (Figure 62).

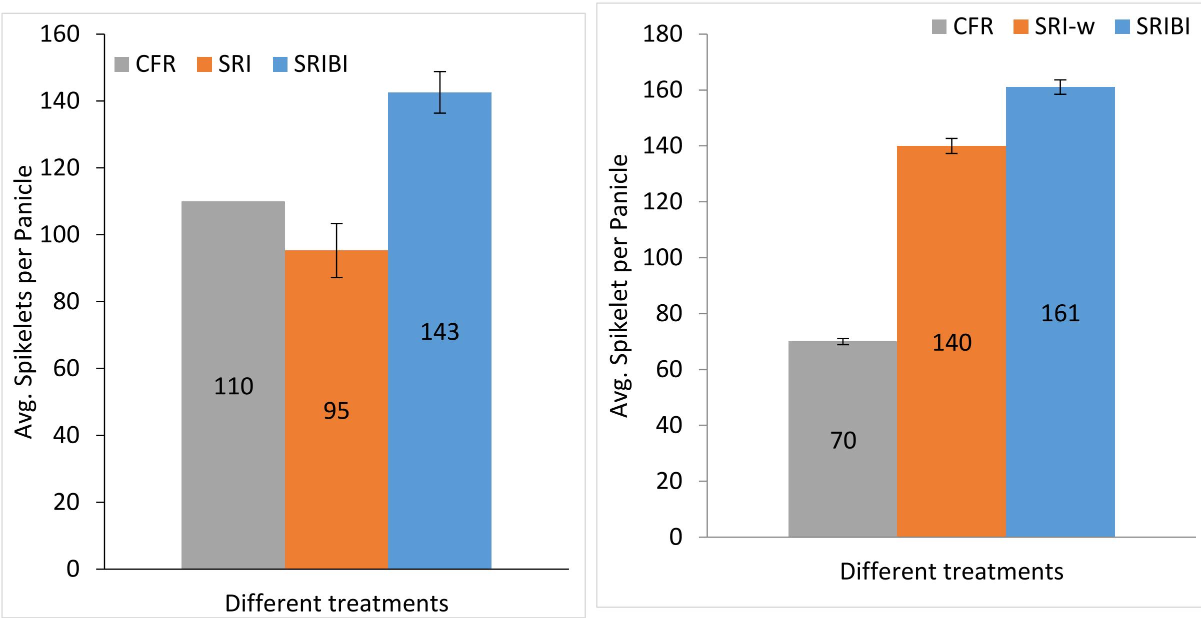



*Figure 61. A comparison of spikelets per panicle in CFR, SRI, and SRIBI (Left: 2019; Right: 2020)*

*Grain weight*

The 1000 grain weight was similar for SRI and SRIBI to a large extent, showing that intercropping did not affect quality of the grain in rice (Figure 63). Additionally, for the SRIBI system, for every 1000 g of rice, an average of 25 grams of beans was also harvested. This shows that intercropping with rice under SRI can further improve the socioeconomic conditions of farmers as also evidenced by the SRI methodology.

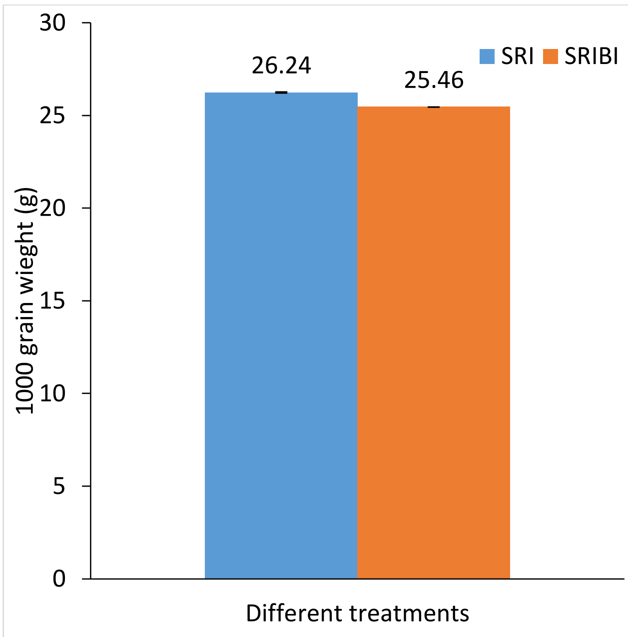



*Figure 62. A comparison of 1000 grain weight in SRI and SRIBI*

In terms of total yield, on average, a 20-30% increase in rice yield was noted in the trials across 2019 and 2020. The average yield in the area is between 2.5 – 3.5 t/ha while as with SRIBI, the yield reported was between 3.7 – 4.6 t/ha (Figure 64).

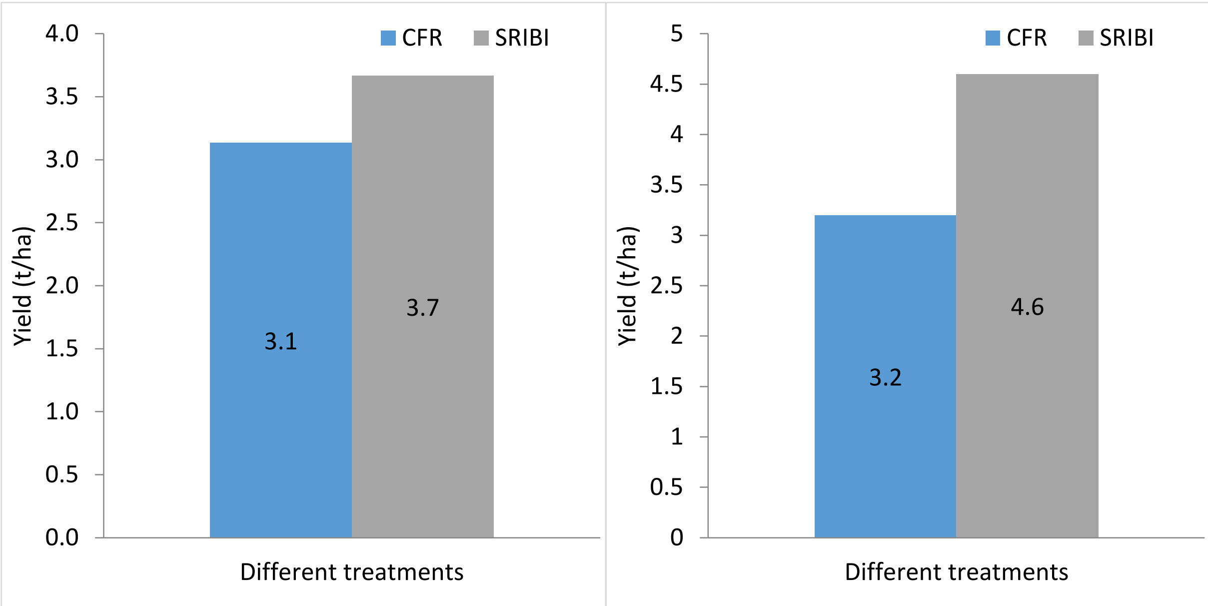



*Figure 63. Yield observed in the different treatments (Left: 2019; Right: 2020)*

*Filled grains per panicle*

The number of filled grains per panicle was counted for the three treatments and intercropping was found to have a positive effect on this parameter, as can be seen in Figure 65.

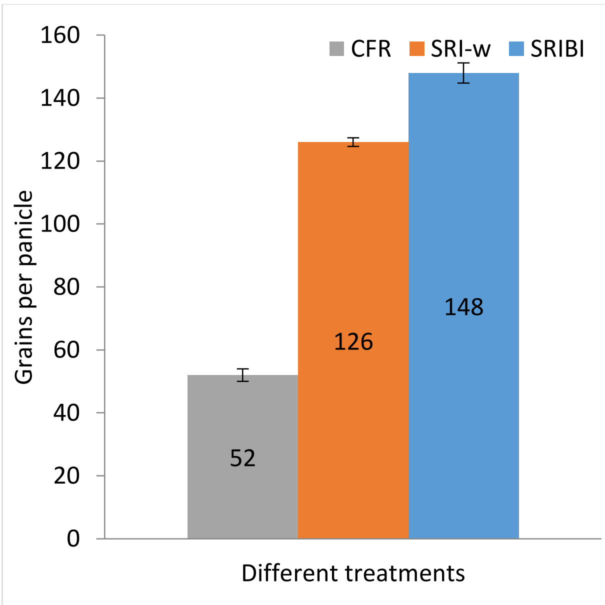



*Figure 64. Grains per panicle observed in the different treatments (2020)*

*Fodder units*

Rice husk is used either as home-made fodder for domestic animals or as a filling material during the packing of horticultural products like apples, hence has a significant economic value for the farmers in the region. In 2019, the number of fodder units per kanal (1 hectare = 20 kanal) in CFR was found to be 90, while as in case of SRI with intercropping, it was found to be 140. While as in 2020, the number of fodder units per kanal under intercropping SRI was found to be 160 (Figure 66). This can be attributed due to the higher number of tillers in case of SRI management practices.

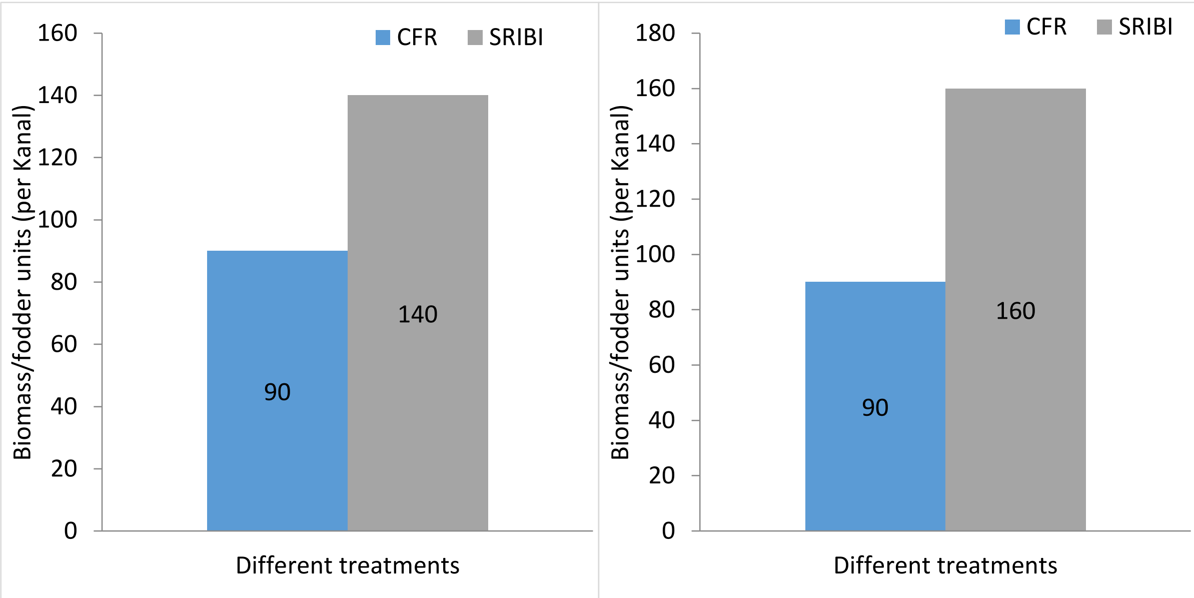



*Figure 65. Number of fodder units observed in the different treatments (Left: 2019; Right: 2020)*

### 4.4.3. Effect of intercropping on weed density

The comparison of weed density was done only between SRI and SRIBI because in case of CFR, herbicides are used conventionally to kill the weeds. In SRI and SRIBI test plots, after the first weeding weeds were allowed to grow in order to make the comparison. In SRIBI, although only about 30% of the beans grew into plants, the effect of the intercrop on the weed incidence and growth was statistically significant ($p \leq 0.05$; $p=0.0048$) (Figure 67). The weed density was 77% lesser in 2019 and 59 lesser in 2020 intercropping treatments compared to the SRI (weedy control). The lesser incidence of weeds in intercropped systems has been well documented in other crop systems before. Kermah et al. (2017) reported a reduced weed density in maize-grain cropping system, while as Liebman and Dyck (1993) and Trenbath (1993) have remarked that weeds and disease may be better suppressed in case of intercropping systems as compared to sole cropping system [386–388]. The findings of this study are also in consonance with the findings of Singh et al. (2007), where it was reported that intercropping with sesbania decreased weed density in case of dry seeded rice [389].

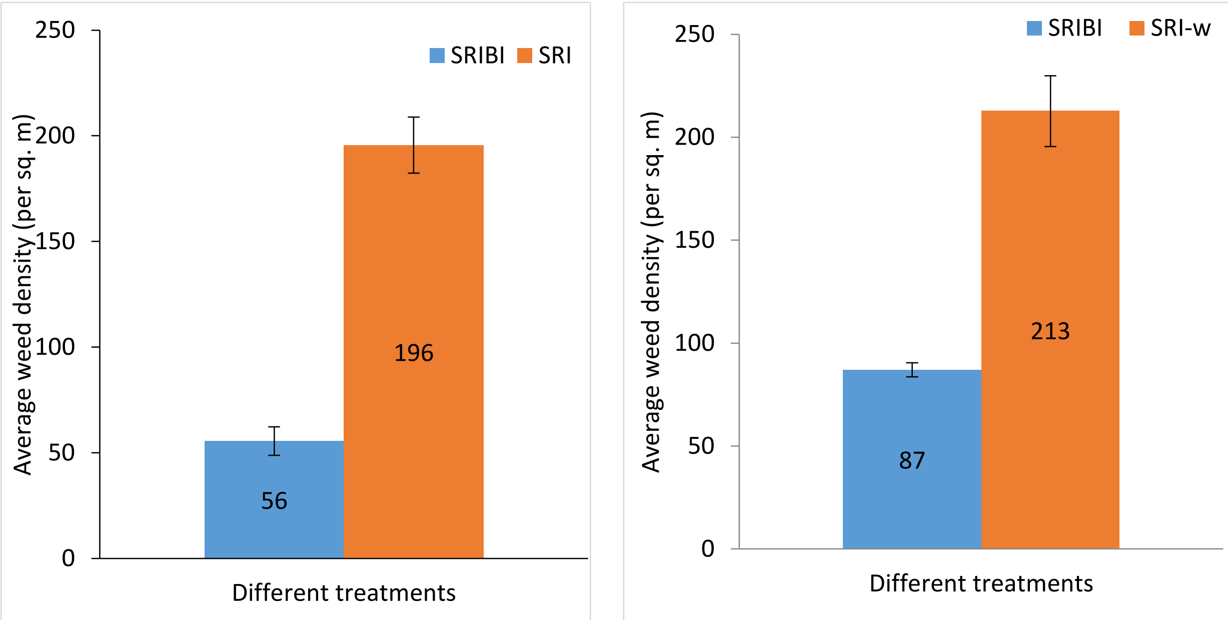



*Figure 66. Weed density comparison between SRI and SRIBI (Left: 2019; Right: 2020)*

Since the incidence of weeds and the labour needed to control them form the two main criticisms of the SRI methodology, it can be deduced from the results of this study that intercropping can be a vital addition to the SRI method.

The following photographs are a visual representation from the experimental plots, showing the difference in the incidence of weeds under SRIBI (Figure 68) and SRI (Figure 69). The average number of weeds per $m^2$ in case of SRIBI and SRI was 56 and 196 respectively, in 2019 (Figure 67) ($p \leq 0.05$; $p=0.0048$). In 2020, the average number of weeds in SRIBI was recorded as 87 per square metre while as for SRI, it was 213 (Figure 67). Among the sampled sites, SRIBI recorded a highest incidence of 56 per plant square and a lowest of 22 per plant square. On the other hand, SRI recorded a highest incidence of 200 per plant square and a lowest of 133 per plant square. A plant square is the square area of land between four rice plants forming the four corners of a square. It can be seen that on an average intercropping legumes reduced the weed population by around 60-70%. Farooq et al. (2017) also studied the suppressing of weed growth using sorghum as intercropped mulch and reported a reduction of weed population by up to 77% [390].

*Figure 67. Weed incidence in a SRIBI plant square*

*Figure 68. Weed incidence in a SRI plant square*

## 4.5. Farmer reflections on the field experiments

The economic balance of the new rice farming system, Rice iCrop, with beans as the intercrop, as seen from the field experiments, is presented in Table 7. The increase in the net earnings of farmers was observed to be 57%. This was accompanied by an increase of 41% in the input costs with a corresponding increase of 51% in the output benefits. The cost of compost constituted 63% of the input costs and this points to the potential of decreasing the inputs costs even further through local production of compost. In this case, the net earnings would be more than double compared to the conventional rice farming system.

*Table 7. Economic balance sheet of the innovations implemented during the course of research*

| | Input | Quantity (per ha) | Cost (INR) | Output | Quantity (per ha) | Benefit (INR) | Earnings (INR) | Increase (%) |
|---|---|---|---|---|---|---|---|---|
| **CFR** | *Seeds* | 400 kg | 6000 | *Rice* | 5600 kg | 84000 | | |
| | *Manure* | 0.33 trolley | 20000 | *Fodder (Rice Straw)* | 1800 units | 72000 | | |
| | *Fertilizer* | 300 kg | 6666 | | | | | |
| | *Pesticides* | n.d. | 4000 | | | | | |
| | *Labour for weeding* | 80 work hours | 5000 | | | | | |
| | *Labour for irrigation* | 200 work hours | 12500 | | | | | |
| | ***Total cost*** | | **54,166** | ***Total benefit*** | | **156,000** | **101,834** | |
| **SRIBI** | *Seeds* | 40 kg | 600 | *Rice* | 7200 kg | 108000 | | |
| | *Manure* | 0.33 trolley | 20000 | *Fodder (Rice Straw)* | 3200 units | 128000 | | |
| | *Compost* | 6000 kg | 48000 | | | | | |
| | *Intercrop Seeds* | 2 kg | 400 | | | | | |
| | *Labour for weeding* | 10 work hours | 660 | | | | | |
| | *Labour for watering* | 100 work hours | 6260 | | | | | |
| | ***Total cost*** | | **75,920** | ***Total benefit*** | | **236,000** | **160,080** | **57,20** |

The practices and the results of the agroecological practices of the System of Rice Intensification and intercropping on one hand appealed to the farming sense of the local farmers, evoking in them old ecological memories associated with farming and on the other hand, sometimes, left them surprised with the results. The response of the farmers to the interventions indicated that farmers are not just fence-sitters when it comes to innovations in the food system. They are the most relevant parties when it comes to the implementation of new strategies. They ask questions, they understand the philosophy behind new interventions, and only then do they put all their heart and soul in the implementation.

The practice of alternate wetting and drying of the rice field under SRI evoked memories of a farming practice in a participating farmer that he had witnessed in a neighbouring village, where a farmer used to dry his rice field before watering it again. Our farmer reported that despite facing ridicule from his fellow farmers for ‘not taking care’ of his rice plot, that farmer had got a rice harvest that ‘had never been seen before’, with 30 panicles per plant. This indicates that the farmers are privy to the workings of agroecological interventions that we as scientists consider as new. The only thing new in such projects is the initiative and incentive that farmers are provided with in order to encourage them to take up these practices. For researchers it may just be another study, but for the farmers on ground it is their food and livelihood.

The concept of compost or mulch wasn’t a new, never heard of before, concept either for the farmers. It was another practice that the farmers already knew of, even knowing the local name for compost (*Boujar*). When we talked about intercropping and mulching with the farmers, the farmers showed an understanding of the concept of nitrogen fixation by the legumes in aid of the rice plants by likening it to composting. This again highlights the importance of traditional ecological knowledge that is present in the sociological subconscious in the farming communities, waiting to be initiativised, in order for it to again benefit the farmers as well the ecology. Once, while introducing the subject of SRI to an elderly couple working their rice field, the old woman farmer asked; “yes, that is fine, but what is the philosophy behind these practices?.” This led to an explanation of the different SRI practices from the project team which ultimately satisfied the farmer to adopt it in her field. That even the unlettered farmers have the capacity to ask questions of the practices being introduced speaks of the responsibility of the researchers and scientists on ground to effectively communicate the right things to the farmers.

The visible plant growth characteristics of rice plants that differed between flooded rice, SRI, and intercropped SRI were duly observed by the farmers who made it a point to visit each other’s farmers to check on and learn from each other. That a single transplanted seedling could produce up to 50 tillers was something impressive and unseen of among the farmers.

*Figure 69. One of the farmer's grandson observing the difference between SRI and SRIBI*

A few observations made by the farmers without any specific inquiry from the project team were about the resilience of the crop against disease and extreme weather. The aromatic rice variant (*Mushkbudij*), a local geographical indicator (GI), grown in the experiments is prone to rice blast, having led to up to 80% yield losses in the past. The disease is normally controlled by the application of insecticides on the panicles at the ripening stage, thus increasing the chance of their residues entering the human food chain. The farmers observed that the occurrence of the disease was generally low in that season but in the SRI plots, this disease did not even appear. Another observation was the effect of rainstorm on the standing crop, with plants in normal crop partly forced to lie down while as the SRI plants stood tall.

It was also found that the agroecological interventions undertaken evoked the entrepreneurial spirit in some of the farmers during the course of the studies. Before delving on this further, it would be pertinent to mention that nowadays farming has been relegated to a sort of subsistence activity or in the worst case, a liability—an activity that has to be done without any realistic expectation of monetary benefits. A common refrain among the farmers is “we spend more on labour and chemical inputs than the benefits we get in terms of yield”. In this regard, the queries of the farmers if they could produce their own compost and set up a composting unit in their locality was indicative of their rejuvenated interest in making the best out of available resources (‘waste’, included). This domino effect of one innovation leading to another is evidential of the applicability and the acceptability of continuous sustainable innovation in rural development.

It also serves to highlight the role, and the importance thereof, of food growers in the direction of achieving the Sustainable Development Goals (SDGs) mandated by the UN.

These experiences led some of the farmers to the decision of continuing with the practices in the next seasons, hence signalling a certain degree of success of the interventions. Also more farmers that were not part of the study asked to be contacted in the coming seasons and were willing to participate in future studies. This hints on one hand at the potential for organic growth of innovative and sustainable farming communities while on the other hand it points to a certain degree of resentment for the status-quo in the cropping systems. From these field reflections, it can be concluded that with the right approach, the ground for sustainable innovations in rural development does not just exist but is a fertile land ready for cultivation of new, synergistic systems.

## 4.6. A decision support model for farmers based on field experiences

In addition to the results summarised in the preceding sections, the experiments are lent valuable experiences to the farmers and the project team, which can guide other farmers in future with respect to the implementation of SRI and intercropping practices in their rice fields. Some of these lessons that can help the farmers make the right decision at the right time are summarised in the following sections.

***Start early***

Facilitators and farmers should get into touch early, well before the rice cultivation season takes off, in order to sort out all the modalities. It should be clear which plots belonging to the farmers shall be used for experiments and the logistical arrangements should be made accordingly. This includes the preparation of nursery, preferably, next to the main field. Since rice seedlings are transplanted young under SRI, it must be made sure that the rice field has been irrigated and the soil is wet by the time seedlings are ready to be transplanted. The rice field should be irrigated a couple of days before the scheduled transplantation, the exact number of days depending on the type of soil in the field. If the field is quick drying then watering it overnight before the day of transplantation could also work. However, if the field is slow drying, then it may be necessary to water it a day or two before transplantation. This needs to be taken care to avoid any problems on the day of transplantation.

***One step at a time***

It is recommended to introduce the innovations step by step in a farmers group. In the context of the innovation under discussion, it is recommended to introduce the SRI methodology of growing rice first and then proceed with intercropping in SRI in the next season onwards, after the results of first interventions are there for the farmers and everyone else to see. It is important for the facilitators to build trust with the community and only with trust can new practices be successfully introduced and implemented. In this regard, it is important that farmers' queries and concerns are taken care of on priority. If scientists are on the frontline of advancing innovation through research and study, it is the farmers that are at the frontline of implementation and adaptation. Without implementation, an innovation cannot just bring about a change!

*Figure 70. An elderly farmers examines his rice harvest*

***The intercropping care***

Since it is recommended to sow the intercropping plant seeds after the first weeding, it is not recommended to dry the field before the first weeding. One can even keep a thin layer of water standing in the field till the first weeding, the exact level of water depending on the type of soil, as explained in the previous section. If the field is allowed to dry before the first weeding, it becomes difficult, almost impossible to do the weeding with the rotary hoe or a conoweeder. It is recommended to sow two seeds at one place between the rice crop rows to reduce the chances of the failure of the intercropping crop by half. Once the seeds have been sown, it is recommended not to flood the field with water so as to provide an aerobic environment for both the crops. An alternate wetting and drying of the field is recommended. Between transplantation of rice and sowing of intercropping plant (legume) seeds a gap of at least two weeks is recommended.

***Reflections and lessons learnt***

It is important to record the reflections of farmers during the course of experiments. Farmers have an eye for specific features of crops that may sometimes go unnoticed to the eyes of the facilitators. Hence it is important to have your eyes and ears open during the course of these experimental studies. These can be the basis for important lessons that can shape future studies.

# 5. CONCLUSIONS

This study makes the case for agroecological innovations in the current rice farming system to address the challenges of food and nutritional security, water scarcity, and soil degradation. In the review part of this study, the theoretical base for this case is made, using previous studies as reference. The vital interrelationships between such innovations and rural development and the Sustainable Development Goals (SDGs) were also established in this part. This is followed by a compilation of the results from the experimental studies that were conducted. Experiments were conducted first at greenhouse chamber level to establish the proof of concept for the relevance of the innovation of intercropping with rice under the System of Rice Intensification (SRI). This was followed by farmer-participative experiments at the field level to test for the scalability of the innovations and to test if intercropping brings the same benefits to rice farming system which it reportedly brings into other cropping systems.

The follow points highlight the main conclusions of this research:

1. Agroecological interventions like the System of Rice Intensification (SRI) and intercropping improve the environmental and economic productivity of rice farming.
2. The SRI has room for innovations which can make it an even better sustainable rice farming alternative.
3. Growing rice under the System of Rice Intensification with Beans Intercropping (SRIBI) improves its different plant growth characteristics and yield.
4. Intercropping (SRIBI) drastically reduces the weed infestation in rice plots grown under SRI regimen.

In the first batch of greenhouse level experiments, it was observed that intercropping resulted in an increase in different plant growth characteristics like plant height and tiller number. It was also observed that rice plants in the intercropping system, System of Rice Intensification with Beans Intercropping (SRIBI) showed higher nutrient uptake, especially nitrogen uptake, and showed a higher chlorophyll content in the leaves as compared to conventional flooded rice (CFR) cultivation as well as the normal SRI. The savings in water consumption and soil water retention in these experiments was also recorded. Further experiments were conducted to find the optimum time and spacing of the intercropped species with respect to the main crop. These aimed at a comparison of SRI and SRI with different configurations of intercropping. The results from the greenhouse experiments were used as the base to design experiments on the field scale.

In the field experiments, the focus of observation was the plant physical characteristics and the yield, to find out if intercropping would affect these characteristics of rice in comparison to SRI. The effect of intercropping on the incidence of weeds was also studied, as weeds are widely considered as a drawback of the SRI method and an increase in the labour requirements under SRI is also attributed to weeds. It was observed that intercropping led to an improvement in the physical growth characteristics of the plants in comparison to both SRI and CFR, despite only about 30% of the beans sown growing into plants. These included improvements in plant height and the spikelet number per panicle (SNPP), which increased by up to 20% and 50 % respectively in SRIBI compared to SRI. The tiller number in SRIBI was multiple times (up to 3 times) higher as compared to the conventionally grown rice. There was no significant difference observed in the grain weight between SRI and SRIBI. The 1000-grain weight was 26.24g and 25.46g for SRI and SRIBI respectively. However, in case of SRIBI, for every 100g of rice, 2.5g of beans was reported.

The marked difference between SRI and SRIBI was however observed in the incidence of weeds between the rows of rice. It was observed that intercropping led to a substantial reduction in weed population, which was clearly visible in the plots. A 77% reduction in the weed population was observed under intercropping as compared to the weed population in SRI, in absence of manual or chemical weeding after the date of intercropping.

The local aromatic rice variety (*mushkbudij*) which was used in the experimental studies is usually prone to rice blast in the ripening stages. However there was no incidence of the diseases in either SRI or SRIBI during the experimental trials, an aspect, that although needs deeper study, is definitely encouraging for the farmers. It was also observed that rice plots under SRI and SRIBI showed better resilience against rainstorms as compared to the neighbouring plots grown under conventional flooded rice (CFR) system.

These results suggest that intercropping legumes with rice under the System of Rice Intensification (SRI) has the potential to improve the ecological security of farming systems while at the same time improving the socio-economic situation of the farmers. This is evident from the improved growth characteristics, yield characteristics, resistance against weeds and extreme weather, and the possible improved resilience against diseases that was observed in these experiments. Such agroecological interventions need to followed up and continued in partnership and cooperation with farmers and organisations working on the ground.

Based on the theoretical and implementational research undertaken in the scope of this study, it can be concluded that SRI is a viable agroecological alternative to the current rice farming system, with a potential to improve the socioeconomic and ecological balance of the world food system. In view of the challenges like water scarcity, soil degradation, and increased occurrence of extreme weather events, SRI shows the required resilience, adaptation, and regeneration potential. Intercropping beans with rice under SRI is a valuable addition to the SRI method; it serves to diversify the income of the farmers and to reduce the biotic and abiotic stresses on the cropping system at the same time. It can be said that intercropping adds more agroecology to the agroecological method of SRI. Rice farming with SRIBI (System of Rice Intensification with Beans Intercropping) under the name Rice iCrop is hence proposed as an alternative sustainable rice farming system.

# 6. RESEARCH OUTLOOK

The results of this study have created scope and provide direction for further studies in this field. On one hand, the new studies could include other aspects of the intercropping system that were not in the scope of the current study. While as on the other hand, some areas of interest that came to light during the course of these studies could also be pursued in further studies. In this regard, the outlook for future research has been summarised below.

## Continued innovation and studies

Future experiments could explore further innovations in the direction established in the current study. These could include intercropping with other plants like medicinal plants and other cover crops. Experimentation with no till farming could also be done with SRI. Additionally, experimental studies could examine the effects of intercropping and SRI on the soil health, which needs years of continuous study of the soil. The effect of these innovations on the nutrient content of rice grains could also be explored. Future studies could also look at the dynamics of greenhouse gas emissions from the rice crop and do a comparison of the three scenarios—CFR, SRI, and SRIBI.

The current study hinted at a possible remediation of disease occurrence in rice plants under SRI management. Hence, the effect of SRI on the disease occurrence in rice farming systems could be studied in detail.

*Figure 71. One of the participant farmers from 2019 preparing his SRI-based rice nursery in April 2020, continuing with the practices introduced last year*

## Composting from kitchen and animal waste

The current study established that intercropping under the SRI regimen provides better economic returns to the farmers. These economic returns can be increased further by making the farming communities self-sufficient in terms of the compost required in their farms. The new interventions increased the input cost by 40%, notwithstanding an overall increase of net earnings by 57%, cost of compost comprised 63% of the total input costs. If the compost is locally produced at the community level, the input costs could be reduced by 50% in comparison to the conventional farming practices, and the net earnings would more than double. This highlights the scope of exploring the potential of local compost production for local consumption.

## Weeding robot as an agroecological intervention

The current study took a step in the direction of answering one of the main reported drawbacks of the SRI, which is the higher incidence of weeds under dry soil conditions. Although intercropping legumes did reduce the incidence of weeds, a non-chemical, low-cost strategy for weeding could still be needed in smallholder SRI-based rice farming systems that do not opt for intercropping. The use of low-cost weeding robots in rice farming systems in particular, or other field crop systems in general, could be explored. This could, on one hand, reduce the need to use agrochemicals to control the growth of weeds and, on the other hand, it could reduce the labour requirements under SRI.

*Figure 72. The programming of weeding robot in progress as part of a student project at Hamburg University of Technology (TUHH)*

## Agroecological Footprint Index – a new approach

There are many approaches in scientific literature that propose ways to quantify the ecological cost of a product. These include indices such as water footprint, carbon footprint, and ecological footprint, which quantify the sustainability of a production process. However, when these indices are applied to agriculture they focus on only one aspect of the agricultural activity, which is the crop yield. In a way, the existing indices encourage input-intensive monocultures that threaten the environment with more degradation. However, with agroecological practices, in addition to producing food, the agricultural activities contribute positively to the environment through various ways. These include through an increase in biodiversity, improvement of soil health, better nutritional value of food, reduced water pollution, carbon sequestration, and reduced greenhouse gas emissions. These positive aspects of agroecology-based agriculture need to be incorporated into a new index that quantifies the sustainability potential of these agricultural practices. This could form the basis of a future study in this direction—the development of a possible agroecological footprint index.

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*"There are still seeds to sow.*
*There is still time before, I bow.*
*There are still plants needing care.*
*There is still food to share.*
*There are still harvests to reap.*
*There are still smiles to see before I sleep."*

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# Appendix A – Data Tables

## 1. Greenhouse experiments

*Table 8. Water use in conventional (CFR) treatments (in litres)*

| | C1 | C2 | C3 |
|---|---|---|---|
| August | 7.42 | 7.42 | 7.42 |
| | 1.20 | 1.20 | 1.20 |
| | 0.80 | 0.60 | 0.88 |
| | 1.00 | 0.90 | 1.20 |
| | 0.90 | 0.60 | 0.90 |
| | 1.70 | 1.20 | 1.55 |
| | 1.20 | 1.00 | 1.00 |
| | 1.00 | 1.00 | 0.70 |
| September | 1.10 | 1.10 | 1.30 |
| | 1.20 | 1.20 | 1.20 |
| | 1.00 | 1.00 | 1.00 |
| October | 2.00 | 2.00 | 2.00 |
| | 1.80 | 1.80 | 1.80 |
| | 0.50 | 0.50 | 0.50 |
| | 1.00 | 1.00 | 1.00 |
| | 1.00 | 1.00 | 1.00 |
| | 0.50 | 0.50 | 0.50 |
| | 0.80 | 0.80 | 0.80 |
| | 0.80 | 0.80 | 0.80 |
| | 0.80 | 0.80 | 0.80 |
| November | 1.20 | 1.20 | 1.20 |
| | 2.40 | 2.40 | 2.40 |
| Total | 31.32 | 27.62 | 28.75 |
| Average | 29.23 | | |

*Table 9. Water use in SRI treatments (in litres)*

| | S1 | S2 | S3 | S4 | S5 |
|---|---|---|---|---|---|
| August | 5.35 | 5.35 | 5.35 | 5.35 | 5.35 |
| | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | 1.3 | 1.3 | 1.3 | 1.3 | 1.2 |
| | 1.2 | 1.2 | 1.5 | 1.3 | 1.2 |
| September | 1.4 | 1.3 | 1.3 | 1.4 | 1.3 |
| | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| | 1 | 1 | 1 | 1 | 1 |
| October | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 |
| | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| November | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| Total | 21.55 | 21.45 | 21.75 | 21.65 | 21.35 |
| Average | 21.55 | | | | |

*Table 10. A comparison of water use in CFR and SRI treatments in mini-plots*

| CFR **A3** | SRI ***C1*** | |
|---|---|---|
| 3000 | 1500 | |
| 200 | 600 | |
| 1150 | 700 | |
| 800 | 700 | |
| 1400 | 1000 | |
| 2650 | 1000 | |
| 2200 | 1200 | |
| 1900 | 1500 | |
| 13300 | 8200 | |
| Savings | 38.35 | % |

*Table 11. Total compost use in CFR treatments in greenhouse experiments*

| Total for all pots | |
|---|---|
| Date | kg |
| 11.08. | 1.5 |
| 15.08. | 0.7 |
| 17.08. | |
| 24.08. | 3 |

| | | |
|---|---|---|
| 28.08. | 1.5 | |
| Total | 6.7 | |
| Kg per pot | **2.23** | |
| N per pot | 24.57 | gram |
| P per pot | 10.05 | gram |
| K per pot | 17.64 | gram |

*Table 12. Total compost used in SRI treatments in greenhouse experiments*

| Total for all pots | |
|---|---|
| Date | kg |
| 07.08. | 6.00 |
| 11.08. | 1.00 |
| 15.08. | 1.60 |
| 24.08. | 4.50 |

| | | |
|---|---|---|
| Total | 13.10 | |
| Kg per pot | 2.18 | |
| N per pot | 24.02 | gram |
| P per pot | 9.83 | gram |
| K per pot | 17.25 | gram |

*Table 13. Nitrogen uptake in the rice plants under SRI intercroppping, SRI, and CFR treatments*

| | SRI+I | | | SRI | | | CFR | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Sample*** | ***S1*** | ***S3*** | ***S11*** | ***S4*** | ***S5*** | ***S41*** | ***C1*** | ***C2*** | ***C3*** | ***C11*** |
| ***N wt.*** | 47.1 | 48 | 45 | 47.2 | 48.15 | 45.6 | 48.4 | 47.7 | 47.8 | 45.7 |
| ***%N*** | **0.81** | **0.56** | **0.70** | **0.78** | **0.52** | **0.62** | **0.45** | **0.64** | **0.62** | **0.60** |
| **Avg. %N** | **0.69** | | | **0.64** | | | **0.58** | | | |
| **Hi. %N** | **0.81** | | | **0.78** | | | **0.64** | | | |

*Table 14. Phosphorous uptake in the rice plants under SRI intercroppping, SRI, and CFR treatments*

| | SRI+I | | | SRI | | | CFR | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Sample*** | ***S1*** | ***S2*** | ***S3*** | ***S4*** | ***S5*** | ***S6*** | ***C1*** | ***C2*** | ***C3*** |
| ***%P*** | 0.181 | 0.414 | 0.326 | 0.22 | 0.32 | 0.26 | 0.056 | 0.222 | 0.22 |
| **Avg. %P** | **0.33** | | | **0.26** | | | **0.22** | | |
| **Hi. %P** | **0.414** | | | **0.32** | | | **0.222** | | |

*Table 15. Potassium uptake in the rice plants under SRI intercropping, SRI, and CFR treatments*

| | SRI+I | | | SRI | | | CFR | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Sample*** | ***S1*** | ***S2*** | ***S3*** | ***S4*** | ***S5*** | | ***C1*** | ***C2*** | ***C3*** |
| ***%K*** | 2.75 | 2.85 | 2.65 | 2.38 | 2.45 | 2.44 | 3.3 | 2.8 | 2.7 |
| **Avg. %K** | **2.75** | | | **2.44** | | | **2.80** | | |
| **Hi. %K** | **2.85** | | | **2.45** | | | **3.30** | | |

*Table 16. Number of tillers at different times (days after transplantation) in different treatments in mini-plots*

| ***No. of tillers*** | | | |
|---|---|---|---|
| 09.08. DOT | 30 DAT | 55 DAT | 120 DAT |
| | **07/09/2018** | **02/10/2018** | **08/01/2019** |
| **DAT** | **30** | **60** | **120** |
| I9-1 | 6 | 11 | 12 |
| I9-2 | 7 | 11 | 13 |
| I9-3 | 6 | 10 | 12 |
| I35-1 | 7 | 11 | 18 |
| I35-2 | 5 | 13 | 14 |
| I35-3 | 6 | 10 | 18 |
| IS-1 | 6 | 14 | 20 |
| IS-2 | 6 | 10 | 18 |
| IS-3 | 8 | 18 | 28 |
| SRI-1 | 7 | 12 | 15 |
| SRI-2 | 8 | 12 | 14 |

*Table 17. Number of tillers at harvest in the different SRI treatments (all replications)*

| *Treatment* | **I9** | | | **I35** | | | **IS** | | | **SRI** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Tillers at harvest* | 14 | 10 | 5 | 6 | 11 | 15 | 17 | 18 | 30 | 5 | 13 |
| | 10 | 12 | 10 | 14 | 11 | 13 | 19 | 20 | 12 | 13 | 14 |
| | 11 | 18 | 13 | 7 | 16 | 9 | | | | 17 | 12 |
| | 11 | 13 | 11 | 18 | 9 | | | | | 16 | 13 |
| *No. of replications* | 12 | | | 12 | | | 6 | | | 8 | |
| | | | | | | | | | | | |
| *Tillers (Avg.)* | **12** | | | **13.00** | | | **19.30** | | | **14.5** | |
| *Tillers (Hi)* | 18 | | | 18 | | | 30 | | | 17 | |

*Table 18. Panicles per plant at harvest in the different SRI treatments*

| *Treatment* | I9 | | | I35 | | | IS | | | SRI | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Panicles per plant* | 10 | 9 | 9 | 5 | 10 | 10 | 13 | 15 | 17 | 6 | 8 |
| | 12 | 13 | 10 | 15 | 15 | 11 | 13 | 17 | 11 | 17 | 10 |
| | 10 | 18 | 7 | 17 | 9 | 9 | | | | 12 | 9 |
| | 10 | 16 | 9 | 9 | 9 | | | | | 13 | 10 |
| *No. of replications* | 12 | | | 12 | | | 6 | | | 8 | |
| *Panicles (Avg.)* | 12 | | | 12 | | | 14.67 | | | 12 | |
| *Panicles (Hi.)* | 18 | | | 17 | | | 17 | | | 17 | |

*Table 19. Chlorophyll content of CFR, SRI, and SRI intercropping treatments*

| *Treatment* | *No.* | $A_{663}$ | $A_{645}$ | $C_{chl\text{-}a}$ | $C_{chl\text{-}b}$ | Avg. $C_{chl\text{-}a}$ | Avg. $C_{chl\text{-}b}$ |
|---|---|---|---|---|---|---|---|
| Seedlings | 1 | 0.7115 | 0.2484 | **8.3679** | **2.3585** | 8.3998 | 2.3935 |
| | 2 | 0.716 | 0.2522 | **8.4148** | **2.4245** | | |
| | 3 | 0.7159 | 0.251 | **8.4167** | **2.3975** | | |
| Flooded | 1 | 0.8457 | 0.3118 | **9.9016** | **3.1823** | 9.3424 | 3.0335 |
| | 2 | 0.7087 | 0.2635 | **8.2917** | **2.7174** | | |
| | 3 | 0.8403 | 0.3115 | **9.8339** | **3.2007** | | |
| SRI | 1 | 0.689 | 0.2547 | **8.0652** | **2.6081** | 9.1519 | 2.8386 |
| | 2 | 0.6569 | 0.2378 | **7.7029** | **2.3713** | | |
| | 3 | 0.9961 | 0.358 | **11.6875** | **3.5365** | | |
| SRI+I | 1 | 1.0506 | 0.3792 | **12.3226** | **3.7669** | 13.1863 | 4.0679 |
| | 2 | 1.2527 | 0.445 | **14.7122** | **4.3279** | | |
| | 3 | 1.0705 | 0.3982 | **12.5242** | **4.1088** | | |

*Table 20. Chlorophyll content of different intercropping treatments and SRI*

| *Treatment* | *No.* | $A_{663}$ | $A_{645}$ | $C_{chl\text{-}a}$ | $C_{chl\text{-}b}$ | Avg. $C_{chl\text{-}a}$ | Avg. $C_{chl\text{-}b}$ |
|---|---|---|---|---|---|---|---|
| Seedlings | 1 | 0.7115 | 0.2484 | **8.3679** | **2.3585** | 8.3998 | 2.3935 |
| | 2 | 0.716 | 0.2522 | **8.4148** | **2.4245** | | |
| | 3 | 0.7159 | 0.251 | **8.4167** | **2.3975** | | |
| I9 | 1 | 1.12 | 0.4018 | **13.1432** | **3.9596** | 11.6611 | 3.2022 |
| | 2 | 1.1237 | 0.3681 | **13.2808** | **3.1706** | | |
| | 3 | 0.7763 | 0.2645 | **9.1475** | **2.4240** | | |
| | 4 | 0.9428 | 0.3348 | **11.0729** | **3.2546** | | |
| I35 | 1 | 1.1891 | 0.4144 | **13.9868** | **3.9248** | 13.1513 | 3.5721 |
| | 2 | 1.209 | 0.398 | **14.2837** | **3.4561** | | |
| | 3 | 0.7045 | 0.2414 | **8.2978** | **2.2310** | | |
| | 4 | 1.3651 | 0.4832 | **16.0370** | **4.6766** | | |
| IS | 1 | 1.29 | 0.4521 | **15.1669** | **4.3159** | 16.2091 | 4.3700 |
| | 2 | 1.6338 | 0.5451 | **19.2829** | **4.8366** | | |
| | 3 | 1.0842 | 0.375 | **12.7606** | **3.5134** | | |
| | 4 | 1.4972 | 0.5162 | **17.6259** | **4.8141** | | |
| SRI | 1 | 0.9336 | 0.3253 | **10.9817** | **3.0801** | 11.3194 | 2.9228 |
| | 2 | 1.1008 | 0.3653 | **12.9975** | **3.2136** | | |
| | 3 | 1.0052 | 0.3352 | **11.8644** | **2.9717** | | |
| | 4 | 0.7999 | 0.2694 | **9.4340** | **2.4257** | | |

## 2. Field experiments

*Table 21. List of farmers and the experimental land area in the field experiments*

| Farmer's name | Land (Kanal) | Date of transplantation |
|---|---|---|
| Gani Bhat | 2.00 | 22.06.2019 |
| Ashraf Dar | 1.50 | 02.07.2019 |
| Bashir Dar | 3.00 | 20.06.2019 |
| Amin Wani | 1.50 | 19.06.2019 |
| Gull Khan | 2.00 | 20.06.2019 |
| Fayaz Mir | 1.50 | 20.06.2019 |
| Afzal Bhat | 1.00 | 04.07.2019 |
| Lateef Bhat | 3.00 | 21.06.2019 |
| Rafiq Dar | 0.50 | 21.06.2019 |
| Ghulam Dar | 0.25 | 20.06.2019 |

*Table 22. Height of plants observed in the field experiments*

| | Plant height | | |
|---|---|---|---|
| | CFR | SRI | SRIBI |
| | 120 | 120 | 110 |
| | 120 | 114 | 121 |
| | 136 | 125 | 118 |
| | 123 | 111 | 110 |
| | 125 | 118 | 118 |
| | 131 | 116 | 120 |
| | 124 | 125 | 130 |
| | 121 | 125 | 128 |
| | 122 | 121 | 124 |
| | 123 | 120 | 131 |
| | 125 | 119 | 148 |
| Average height | 125 | 119 | 123 |
| Max. height | 136 | 125 | 148 |

*Table 23. Panicle length in rice plants observed in the field experiments*

| | Panicle length | | |
|---|---|---|---|
| | CFR | SRI | SRIBI |
| | 23.5 | 19 | 23.5 |
| | 24 | 19.5 | 24 |
| | 22.5 | 22 | 22 |
| | 25 | 20 | 22 |
| | 24.5 | 25 | 21 |
| | 23 | 24 | 22 |
| | 23.5 | 24 | 21 |
| | 22.5 | 21.5 | 22.5 |
| | 24 | 21 | 23 |
| | 23.5 | 22 | 21 |
| Average | 24 | 22 | 22 |

*Table 24. Weed density (WD) in SRI and SRI with intercropping*

| WD (30 cm x 30 cm = 900 cm$^2$) | | WD per m$^2$ | |
|---|---|---|---|
| SRIBI | SRI | SRIBI | SRI |
| 9 | 13 | 100 | 144 |
| 5 | 29 | 56 | 322 |
| 4 | 12 | 44 | 133 |
| 2 | 18 | 22 | 200 |
| 5 | 16 | 56 | 178 |
| 6 | 21 | 67 | 233 |
| 5 | 20 | 56 | 222 |
| 5 | 14 | 56 | 156 |
| 4 | 16 | 44 | 178 |
| | Average | 56 | 196 |

*Table 25. Number of tillers in CFR and SRI treatments*

| | Number of tillers | |
|---|---|---|
| | CFR | SRIBI |
| | 8 | 20 |
| | 14 | 18 |
| | 8 | 28 |
| | 10 | 21 |
| | 9 | 39 |
| | 8 | 32 |
| | 10 | 26 |
| Average | 9.57 | 26.29 |

*Table 26. Data on 1000 grain weight in SRI and SRI intercropping*

| | SRI | SRIBI |
|---|---|---|
| | 2.7056 | 2.5488 |
| | 2.5363 | 2.6003 |
| | 2.5954 | 2.5092 |
| | 2.6851 | 2.5258 |
| | 2.5118 | 2.5526 |
| | 2.7127 | 2.5391 |
| Avg. 100 grain wt. | 2.6245 | 2.5460 |
| Avg. 1000 grain wt. | 26.24 | 25.46 |

*Table 27. Spikelets per panicle in SRI and SRI intercropping*

| | SRIBI | SRI |
|---|---|---|
| | 135 | 96 |
| | 112 | 123 |
| | 159 | 122 |
| | 131 | 84 |
| | 146 | 70 |
| | 165 | 66 |
| | 118 | 106 |
| | 166 | 92 |
| | 151 | 98 |
| Avg. Spikelets per panicle | 143 | 95 |

## Appendix B – Figures

*Figure 73. A photograph of the first experimental set up at greenhouse level (2017)*

*Figure 74. Rice grains germinated under warm and moist conditions*

*Figure 75. A photograph of the second experimental batch at greenhouse level (2017/18)*


*Figure 76. A view of SRI nursery setup in the first field experiments (2017)*

*Figure 77. A view of a well grown rice nursery under SRI management (2017)*

*Figure 78. Transplanted rice field under SRI management (Top: Day of transplantation; Bottom: Three weeks after transplantation) (2017)*

*Figure 79. Top: Preparation of the land for transplantation. Middle: Land ready for transplantation with bunches of rice plants waiting to be transplanted. Bottom: Rice plots rendered dry due to water scarcity (2018)*

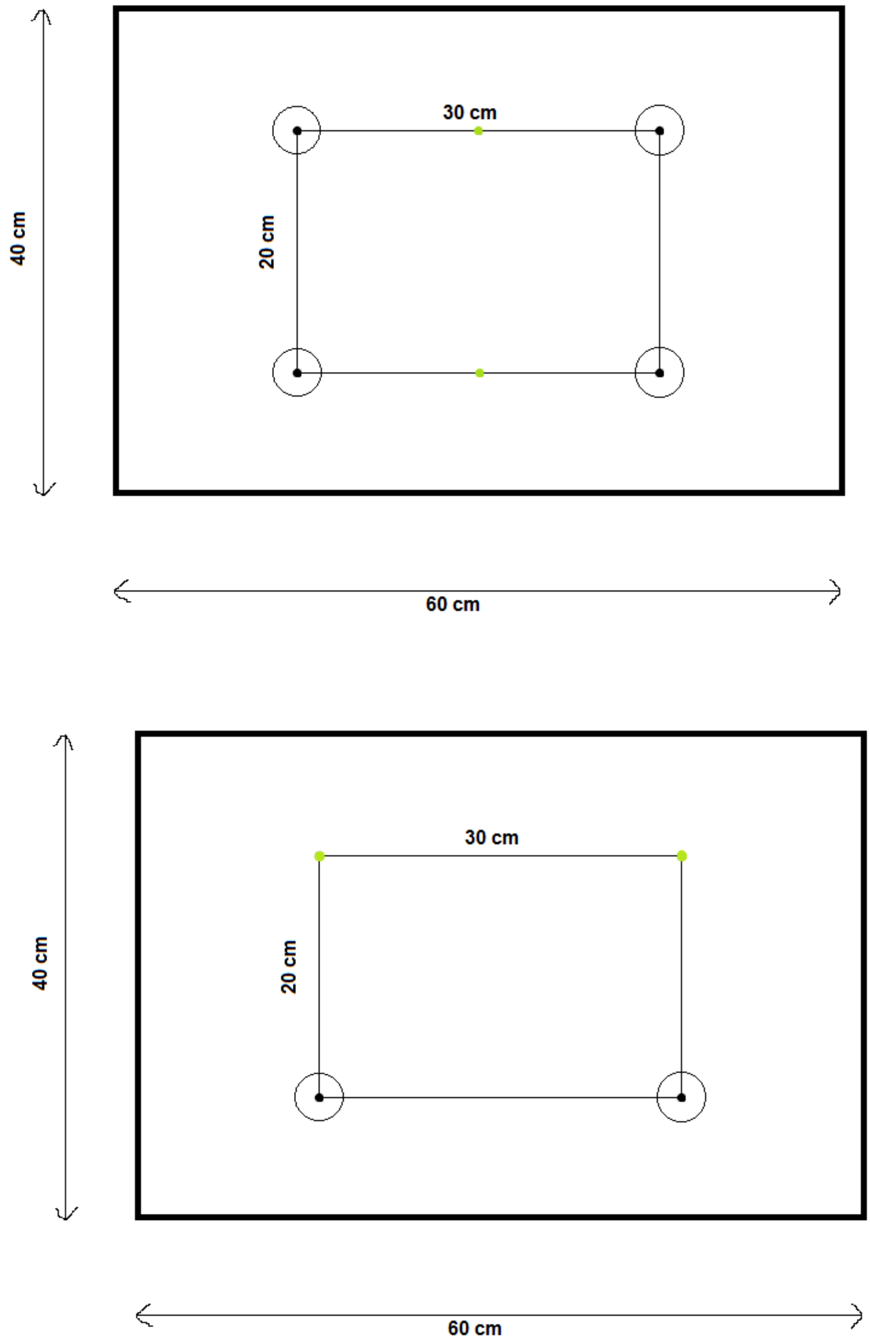



*Figure 80. Graphical representation of the fourth batch of greenhouse experiments. Top: Intercropping with beans (green dots) intercropped between rows of rice (black dots). Bottom: Strip intercropping with beans intercropped in a separate row (2018/19)*

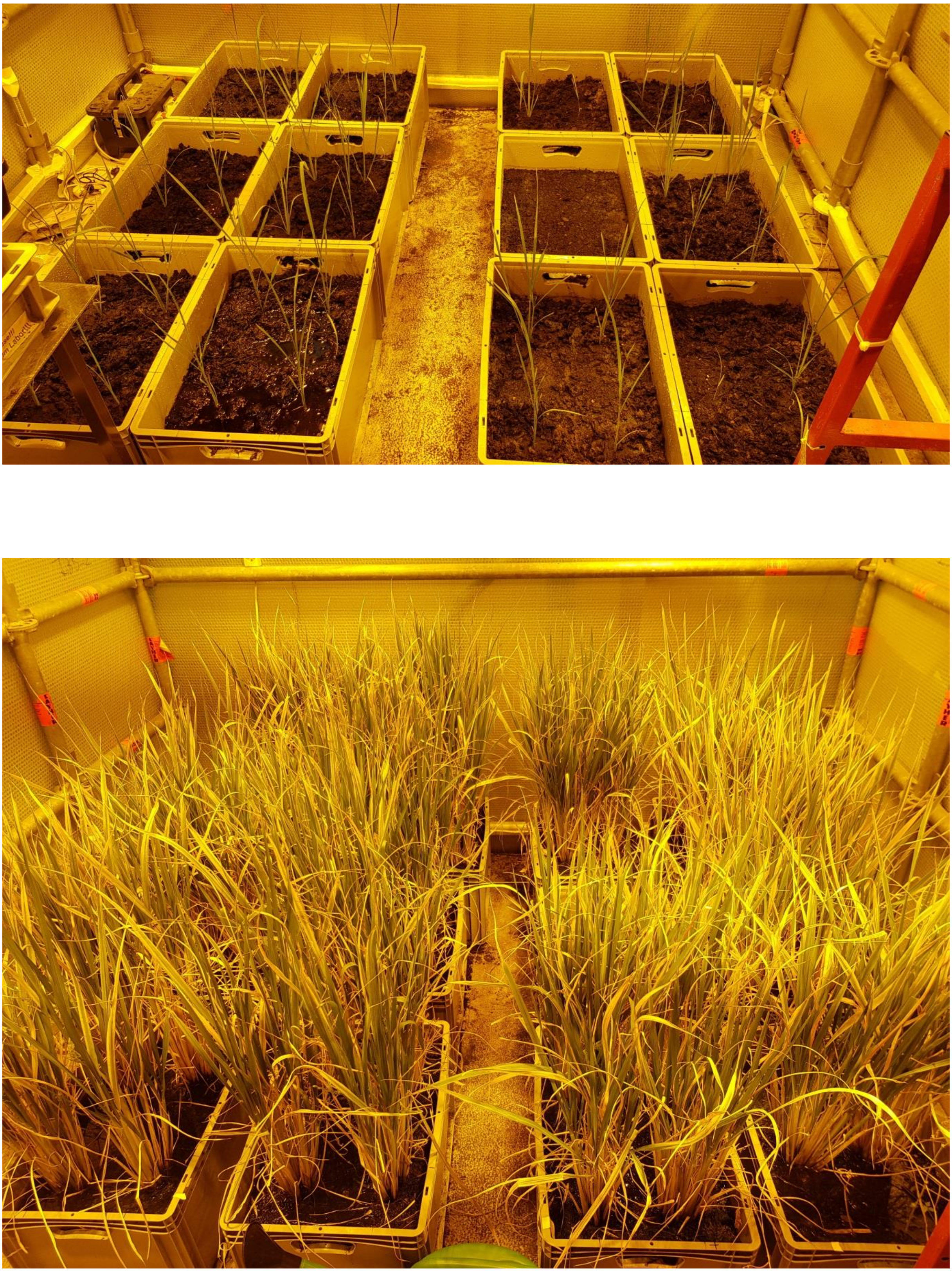


*Figure 81. A photograph of the miniplots after transplantation (Top) and before harvest (Bottom) (2018/19)*

*Figure 82. Meetings with the farmers participating in the field experiments (Top). Bottom: Preparation of the SRI nursery for field experiments (2019)*

*Figure 83. A view of the SRI nursery with rice seedlings/plants ready to be transplanted (2019)*

*Figure 84. Transplantation of the rice seedlings under SRI management*

*Figure 85. Top: Transplantation under SRI management. Bottom: Weeding followed by sowing of intercropping seeds*

*Figure 86. From sowing to growing. Top: Sowing beans in between rows of rice. Bottom: Intercropped plant growing between rice plants*

*Figure 87. A view of the beans growing between the rice plants*

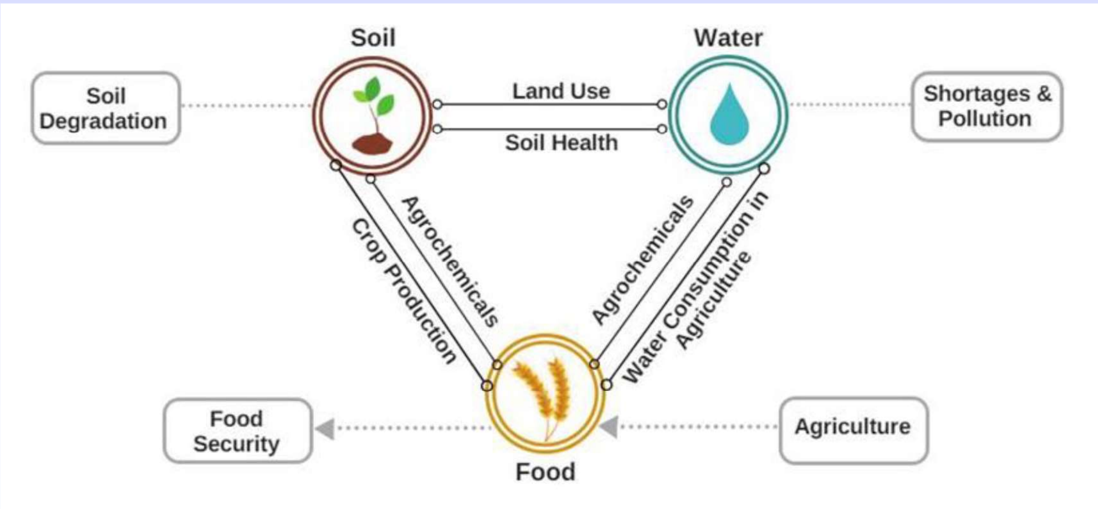
*Figure 88. Top: A SRI plot in the background with a CFR plot in the front. (SRI transplanted 2 weeks later)*

*Figure 89. Synergy: Ready to harvest beans and rice grown under the innovative SRIBI (System of Rice Intensification with Beans Intercropping) management*

**Institute of Wastewater Management and Water Protection**

**Hamburg University of Technology**

**The ecological consequences of industrial agriculture and the pace at which the natural resources of soil and water are being exhausted, make a rethink of food systems imperative. Rice being the staple for more than half the world population and a major water consumer crop can play a vital role in this. This work builds the case for agroecological interventions in rice farming to mitigate the negative impacts of the food system on the environment, to attain sustainable development in rural areas. In this regard, the improvements in plant growth parameters and plant health conditions observed under SRIBI (System of Rice Intensification with Beans Intercropping) are reported. Rice iCrop, based on SRIBI, is presented as an alternative rice farming system due to its wide-ranging socioeconomic and ecological benefits.**

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