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Preface

We would like to present, with great pleasure, the volume-11, Issue-12, December 2025 of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series *in the field of Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

This journal was envisioned and founded to represent the growing needs of Environmental & Agriculture as an emerging and increasingly vital field, now widely recognized as an integral part of scientific and technical investigations. Its mission is to become a voice of the Environmental & Agriculture community, addressing researchers and practitioners in below areas.

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Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with *IJOEAR*. We are certain that this issue will be followed by many others, reporting new developments in the Environment and Agriculture Research Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOEAR* readers and will stimulate further research into the vibrant area of Environmental & Agriculture Research.

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Academic Qualifications: B.Sc. (Horticulture), M.Sc. (Post-Harvest Technology of Horticultural Crops), Ph.D. (Horticulture)

Assistant Professor (Senior Scale - IX), College of Horticulture, Mojerla, Sri Konda Laxman Telangana State Horticultural University, Telangana, India

Dr. Jadala Shankaraswamy is an Assistant Professor (Senior Scale – IX) at Sri Konda Laxman Telangana State Horticultural University, Telangana, India. His research focuses on post-harvest technology, phytochemistry, nanobiotechnology, and value addition in horticultural crops. He has contributed to innovative product development, holds patents in horticultural science, and has received several national and international awards for his research excellence.

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Prof. Özhan ŞİMŞEK

Agriculture Faculty, Department of Horticulture, Çukurova University, Adana, 01330 Turkey.

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Dr. Smruti Sohani

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Dr. Ajeet singh Nain

Working as Professor in GBPUA&T, Pantnagar-263145, US Nagar, UK, India.

Dr. Salvinder Singh

Presently working as Associate Professor in the Department of Agricultural Biotechnology in Assam Agricultural University, Jorhat, Assam.

Dr. Salvinder received MacKnight Foundation Fellowship for pre-doc training at WSU, USA – January 2000-March 2002 and DBT overseas Associateship for Post-Doc at WSU, USA – April, 2012 to October, 2012.

Dr. V K Joshi

Professor V.K.Joshi is M.Sc., Ph.D. (Microbiology) from Punjab Agricultural University, Ludhiana and Guru Nanak Dev University, Amritsar, respectively with more than 35 years experience in Fruit Fermentation Technology, Indigenous fermented foods, patulin ,biocolour ,Quality Control and Waste Utilization. Presently, heading the dept. of Food Science and Technology in University of Horticulture and Forestry, Nauni-Solan (HP), India.

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M.Sc. (Ag.), PhD, FSTA, FSIESRP, Assistant Professor, Department of Seed Science and Technology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia. W.B., India. He received CWSS Young Scientist Award-2016, conferred by Crop and Weed Science Society, received Best Young Faculty Award 2019 conferred by Novel Research Academy, received Innovative Research & Dedicated Teaching Professional Award 2020 conferred by Society of Innovative Educationalist & Scientific Research Professional, Chennai.

Dr.Chiti Agarwal

Dr. Chiti Agarwal works as a postdoctoral associate at the University of Maryland in College Park, Maryland, USA. Her research focuses on fungicide resistance to fungal diseases that affect small fruits such as strawberries. She graduated from North Dakota State University in Fargo, North Dakota, with a B.S. in biotechnology and an M.S. in plant sciences. Dr. Agarwal completed her doctorate in Plant Pathology while working as a research and teaching assistant. During her time as a graduate research assistant, she learned about plant breeding, molecular genetics, quantitative trait locus mapping, genome-wide association analysis, and marker-assisted selection. She wants to engage with researchers from many fields and have a beneficial impact on a larger audience.

DR. Owais Yousuf

Presently working as Assistant professor in the Department of Bioengineering, Integral University-Lucknow, Uttar Pradesh, India.

Dr. Vijay A. Patil

Working as Assistant Research Scientist in Main Rice Research Centre, Navsari Agricultural University, Navsari. Gujarat- 396 450 (India).

Dr. Amit Kumar Maurya

Working asJunior Research Assistantin the Department of Plant Pathology at Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, U.P. India.

Prof. Salil Kumar Tewari

Presently working as Professor in College of Agriculture and Joint Director, Agroforestry Research Centre (AFRC) / Program Coordinator in G.B. Pant University of Agric. & Tech., Pantnagar - 263 145, Uttarakhand (INDIA).

Dr. S. K. Jain

Presently working as Officer Incharge of All India Coordinated Sorghum Improvement Project, S. D. Agricultural University, Deesa, Gujarat.

Dr. Deshmukh Amol Jagannath

Presently working as Assistant Professor in Dept. of Plant Pathology, College of Agriculture polytechnic, NAU, Waghai.

Mr. Anil Kumar

Working as Junior Research Officer/Asstt. Prof. in the dept. of Food Science & Technology in Agriculture & Technology, Pantnagar.

Mr. Jiban Shrestha

Scientist (Plant Breeding & Genetics)

Presently working as Scientist (Plant Breeding and Genetics) at National Maize Research Programme (NMRP), Rampur, Chitwan under Nepal Agricultural Research Council (NARC), Singhdarbar Plaza, Kathmandu, Nepal.

Mr. Aklilu Bajigo Madalcho

Working at Jigjiga University, Ethiopia, as lecturer and researcher at the College of Dry land Agriculture, department of Natural Resources Management.

Mr. Isaac Newton ATIVOR

MPhil. in Entomology, from University of Ghana.

He has extensive knowledge in tree fruit orchard pest management to evaluate insecticides and other control strategies such as use of pheromone traps and biological control to manage insect pests of horticultural crops. He has knowledge in agronomy, plant pathology and other areas in Agriculture which I can use to support any research from production to marketing.

Mr. Bimal Bahadur Kunwar

He received his Master Degree in Botany from Central Department of Botany, T.U., Kirtipur, Nepal. Currently working as consultant to prepare CCA-DRR Plan for Hariyo Ban Program/CARE in Nepal/GONESA.

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Evaluation of Seven Elite Rhizobial Inoculants on It99k5731-1 Cowpea Variety in Soils of Minna Niger State of Nigeria

AHAR, J. I.[1*]; OSUNDE, A.O.[2]; BALA, A.[3]

[*1]Department of Soil Science, College of Agronomy, Joseph Sarwaun Tarkaa University Markurdi, Benue State, Nigeria
[2]Department of Soil Science and Land Management, School of Agriculture and Agricultural Technology, Federal University of Technology, P.M.B 65, Minna, Niger State Nigeria
*Corresponding Author

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Abstract— *Cowpea (Vigna unguiculataL. Walp) is an important source of dietary protein for man, animals and improves soil fertility through biological nitrogen fixation. However, its production potential is limited by a number of factors, one which may be low availability of Nitrogen in the soil which could partly be due to the inadequate numbers of effective rhizobial strains in some soils to fix the required nitrogen. Evaluation of seven rhizobial strains was carried out on yield and yield parameters of cowpea variety IT99K573-1-1 during the cropping season. Prior to the commencement of the trial, soil samples were collected (0 -15cm^2) from each filed and processed for routine soil analysis. The field trials were conducted in Randomized Complete Block Design (RCBD) with nine treatments replicated at five different locations in Minna. Each of the treatment plots was 36m^2 consisting of six manually made ridges of 6m long and an inter-ridge spacing of 80cm. The treatments were; control (no inoculation nor N fertilizer), 60kgNha^{-1}, rhizobial inoculants strains 2NAG53e, 2NAG91a, 2NAG9d, 2NAG5261, CB756 (ref), BR3262(ref) and BR3267(ref). Cowpea seeds were mixed with the inoculants as treatment at planting. All plots received a dose of 30kgPha^{-1} (as Single Super Phosphate) at planting. Destructive sampling was done at 50% flowering to obtain data on number of nodules, nodules dry weight and shoot dry weight. Data was collected for Pod load, pod weight, 100 seed weight, and grain yield at full maturity. From the fertility and suitability rating all the fields had one or two limiting factor for crop production. There was a significant difference between 2NAG5261and the 60kgNha^{-1} treatment but all treatments were not significantly different from the control in terms of number of nodules. However, there was no significant difference at (P<0.05) in all inoculated plants, urea fertilized plants and the control. Statistically, there was also, no significant difference at (P<0.05) in all inoculated plants, urea fertilized plants and the control in terms of nodule dry weight. There was a significant different (P<0.05) between strain 2NAG9d and BR3267(ref) but there was no significant different between the control and all the inoculated plants in shoot dry weight. Higher mean value obtained from plants treated with 2NAG9d, indicated percentage increase in shoot dry weight but was not significantly different from the control and the urea supplied plants. Means of statistical analysis indicated no significant difference (P<0.05) for pod weight per plant among all the treatments and the control. The 60kgNha^1 treatments, rhizobia strains CB756(ref), 2NAG91a 2NAG53e, and 2NAG9d gave the highest mean values of (1067.2kg, 883.9kg, 878.9kg, 832.8kg and 819.4kg) respectively which were more than the control that had a mean value of 769.4kg. Statistically, there was no significant difference between the control and other treatments. There was no response to inoculation in terms number of nodules, nodules dry weight, shoot dry weight, pod weight per plant, pod weight per kilogram per hectare, one hundred seed weight and total grain yield of IT99K-573-1-1 cowpea variety. The evaluation of these inoculants should also be conducted using other cowpea varieties and other legumes in other places outside Minna in order to capture the differences that may exist in physical, chemical and biological properties of soils because inability of cowpea to respond to inoculation could be attributed not only to the crop variety but also environmental conditions and can be site specific.*

Keywords— Cowpea (IT99K573-1-1), Rhizobial inoculants, Biological nitrogen fixation, Nodulation, Shoot dry weight, Grain yield, Soil fertility, Minna (Niger State), Symbiotic effectiveness, Legume–rhizobia interaction.

I. INTRODUCTION

Cowpea is a very important leguminous crop which serves as a major source of protein for man and his livestock in developing countries like Nigeria and even some developed countries (Singh 2005; Langyintuo *et al*., 2003). It is one of the legume crops commonly sown in rotation with both cereals and tubers to replenish nitrogen content of soil, reduces soil erosion and weeds as a cover crop (Sanginga *et al*., 2003).

Despite its environmental and economic contributions to human existence its production in Nigeria and other developing countries is still 50% below its estimated yield potential (FAO 2012). Many researchers and farmers attribute low yield of cowpea to degraded soil fertility, poor agronomic management and inadequate indigenous rhizobial strains in the soil to effectively convert the atmospheric nitrogen in a usable form through a symbiotic relationship between the cowpea and rhizobia. The application of urea fertilizer has many economic limitations but cowpea has the ability under favorable conditions to derive 65% to 70% accumulated nitrogen from biological nitrogen fixation (Jensen, 1997) which can lead to improved shoot biomass and consequently improved yield parameters and total cowpea yield. Many soils however, do not have adequate amount of native rhizobia in terms of quality or effectiveness to enhance biological nitrogen fixation (FAO, 2012). Adler (2008) also suggested that due to the facts that inoculants price is low compared to the potential benefits it provide, farmers should be encourage to inoculate legumes with effective strains. These situations call for the use of inoculants that are symbiotic effective and can enhance cowpea nodulation, growth and yield. Therefore, the objective of this research was to evaluate the effect and symbiotic effectiveness of seven elite rhizobia inoculants on yield and yield parameters of cowpea variety IT99K573-1-1 in Minna, Niger State of Nigeria.

II. MATERIAL AND METHOD

2.1 Study sites:

A field experiment was conducted in Minna, Niger state of Nigeria. Minna lies within the southern Guinea Savanna Zone of Nigeria, (9^0 41N and Longitude 6^0 30E) and has sub-humid tropical climate with a mean annual rainfall of 1200mm (90% of the rainfall is between the month of June and August). The temperature rarely falls below 22^0C and the peak are 40^0 (February to March) and 36^0C (November to December. (Juo, 1998). The experiment was carried out on five farmers' fields within a distance of not less than 20 kilometer apart around Minna. The Fields were located at Gidan Kwano($9^0$31' 589" N and 6^0 26'284" E), Kodoko ($9^0$34' 855" N and 6^0 32' 422" E), Sauka Kahuta (9^0 32' 99" N and 6^0 32' 432" E), Tutungo (9^0 30; 385" N and 6^0 35' 474" E) and Gurusu (9^0 37'917" N and $6^0$38' 877" E)

2.2 Soil Sampling and analysis:

Soil samples were collected at eighteen (18) different points within each field at a depth of 0-15cm. The samples were bulked, thoroughly mixed to form a composite and sub- samples of the composite were taken for routine analysis. Soil samples were air dried and the aggregates were gently crushed and sieved through 2mm and 0.5mm screens for physical and chemical analysis Soil particle size was determined using the boyoucous hydrometer method, Soil pH in H_2O and $CaCl_2$ was determined using glass electrode pH-meter, Walkley and Black method was applied to determine organic matter content, Micro-Kjeldahl digestion procedure was used to determine total Nitrogen, Bray P1 method was applied to determine the available phosphorus, Exchangeable bases (Ca^{2+} Mg^{2+} Na^+ K^+) were extracted with ammonium acetate and determined using Atomic Absorption Spectrophotometer, Exchangeable acidity was extracted with INKCl and determined by titrimeric method, Effective cation exchangeable capacity (ECEC) was obtained by the summation method.

2.3 Field trials:

2.3.1 Land preparation, Experimental design and treatments:

Each of the five farmers' fields used for trial served as replicate. The fields were cleared and ridging was done manually. Each field (replicate) had nine plots, and each plot measured $36m^2$. Each field had a total land area of $324m^2$ ($0.324ha^{-1}$). The treatments were; control (no inoculation nor N fertilizer), $60kgNha^{-1}$, 2NAG53e, 2NAG91a, 2NAG9d, 2NAG5261, CB756(ref), BR3262(ref) and BR3267(ref) strains of bacteria

2.3.2 Planting and crop management:

Cowpea seeds of variety IT99K573-1-1 and all the inoculants were obtained from International Institute of Tropical Agriculture (IITA) Kano substation. The seeds were thoroughly mixed with different inoculants prior to planting. Seeds were planted at rate of four seeds per hole and were later thinned to two plants per stand two weeks after planting. Single Supper Phosphate (SSP) was applied at the time of planting of cowpea in all the plots and fields at the rate of $30kgP_2O_5/ha^{-1}$. Manual weeding was done at two and six weeks after planting while combat insecticide was used to control insect pest at 800ml per hectare.

2.4 Data collection and Analysis:

Numbers of nodule were counted at 50% flowering by destructive sampling; nodules dry weight, and shoot dry weight were also weighed. Symbiotic effectiveness (SE) and Response to inoculation were calculated using:

$$\%SE = \frac{DwI}{DWN} * 100 \quad (1)$$

Where DWI= Dry weight of inoculated shoot, where DWN =Dry weight of nitrogen applied plants

Response to inoculation (RI) was calculated using the formula

$$\%RI = \frac{DWI - DWU}{DWU} * 100 \quad (2)$$

Where DWI = Dry Weight of Inoculated shoot, where DWU = Dry Weight of un-inoculated shoot

The data was subjected to statistical analysis using analysis of variance (ANOVA) Statistical Analysis System (SAS) version 9.2 Software (SAS, 2009), while the means were separated using the Least Significant Difference (LSD) at 5% level of probability.

III. RESULTS AND DISCUSSION

Results show that the soil texture in all the five fields is loamy sand. The soil texture was suitable for cowpea cultivation as also, observed by Dugje *et al.* (2009) that loamy sand and sandy loam gives the best yield. All pH results from the farmer fields as shown in table I fall between 6.2 to 7.6 for pH (H_2O) and 5.0 to 5.9 for pH ($Cacl_2$). Fanton *et al*, (1993), and Fanton and Helyar (2007) stated that soil pH from 5.0 to 9.0 is a range for availability of most macro and micro nutrients. Therefore, pH of the soils does not affect the availability of any nutrient element in the soil and the pH range was good for nutrients availability because at this level also most microbes are available for nutrient cycling.

The organic carbon of the five fields ranged from 1.03- $2.507gKg^{-1}$.This shows that organic carbon in Gidankwanu, Kodoko, Saukakahuta and Tutungu was moderate, only Gurusu had high amount of carbon with a value of 2.51g/kg as shown in the table below. Moderate amount of organic carbon could be due to high amount of decomposable plants materials in the soil that can sequester carbon. The amount of carbon and nitrogen in an environment will depend on the quantity and quality of plant materials in the soil. This finding contradicts the generalization by Aliyu (2013) who observed low organic carbon and very low total nitrogen as common feature of savanna soil.

Nitrogen was low in Gidankwanu and Gurusu with 0.15g/kg and 0.12g/kg respectively. In kodoko, Saukakahuta and Tutungu available nitrogen was moderate with 0.16g/kg, 0.18g/kg and 0.19g/kg respectively.

Available P was moderate only in Gidankwanu with 9.09mg/kg. P was low in kodoku,Saukakahuta, Tutungu and Gurusu with values ranged from 2.22mg/kg, 5.35mg/kg, 3.82mg/kg and 5.29mg/kg respectively.

The exchangeable cations, Na was high in Gidankwanu, Kodoko, Sauka and Gurusu and moderate in Tutungu, Ca was low in Gidankawnu, Saukakahuta, and Tutungu but moderate in Kodoko and Gurusu. K was high in Kodoko, Saukakahuta and Tutungu while it was very high in Gurusu and moderate in Gidankwanu. Mg moderate in Gidankwanu, Saukakahuta and Tutungu but was high in kodoko and Gurusu with values as shown in the table1 below.

The Effective Cation Exchange Capacity was low in G.k, Suakakahuta and Tutungo moderate in kodoko and Gurusu with 15.5 and 17.5 values respectively as shown in Table 1.

From the fertility and suitability rating all the fields have one or two limiting factor for crop production. Phosphorus is moderate in Gidankwanu while, Na is low Gidankwanu. Fertility rating was done based on soil fertility rating by Esu (1991) and Shehu *et al.* (2015)

TABLE 1
PHYSICAL AND CHEMICAL PROPERTIES OF THE FARMERS' FIELD USED FOR THE TRIAL

Soil parameters	GidanKwano	Kodoko	Saukakahuta	Tutungo	Gurusu
Sand (gKg^{-1})	730	770	770	750	690
Silt (gKg^{-1})	100	100	100	100	140
Clay (gKg^{-1})	170	130	130	150	170
Textural class	LS	LS	LS	LS	LS
pH(H_2O)	6.2	7.61	6.71	6.29	6.48
pH($CaCl_2$)	5.1	5.9	5.4	5.3	5
Organic Carbon (gKg^{-1})	1.32	1.07	1.03	1.71	2.51
Total Nitrogen (gKg^{-1})	0.15	0.16	0.18	0.19	0.12
Available Phosphorus (mg/Kg)	9.09	2.22	5.35	3.82	5.29
Xchangeable cations($cmol^{+}Kg^{-1}$)					
Ca	4.45	6.66	4	4.89	6.66
Mg	2.14	5.92	1.38	2.81	7.32
K	0.52	1.74	1.5	1.01	2.65
Na	1.24	1.15	0.77	0.64	0.73
Exchangeable Acidity	0.2	0.25	0.2	0.2	0.2
ECEC	8.35	15.47	7.65	9.35	17.35

3.1 Number of Nodules (NN):

There was significant difference ($P<0.05$) between rhizobia strain 2NAG5261, 2NAG53e and 2NAG9d but all treatments were not significantly different from the control in terms of number of nodules. The 2NAG5261treatment gave the highest number of nodules than the control but there was no significant difference between the treatments and the control. There was also a significant difference between 2NAG5261and the $60kgNha^{-1}$ treatment. This shows the promoting and positive impact of effect of this 2NAG5261 nitrogen source treatment over chemical nitrogen application on number of nodules in plants which is agreement with the finding by Manish *et* al (2011). Lack of response to inoculation in terms number of nodules found in other treatments could be attributed to low concentration of phosphorus in the soil or it can also signifies that the population of the indigenous rhizobia was higher and highly competitive than the introduced strains.

3.2 Nodule dry weight (NDW):

Statistically there was no significant difference at ($P<0.05$) in all inoculated plants, urea fertilized plants and the control. Plants treated with rhizobia strained 2NAG5261produced the highest mean value for number of nodules but could not translate in to the highest nodule dry weight. This is because the numbers of nodule were many but their size was not big to translate into higher weight. This agrees with Chiamaka (2014) which proved that the difference between nodule dry weight of an inoculated plant could be due to the ability of the most effective introduced rhizobia strain to produce bigger size of nodules. Nyoki and Ndakidemi (2014) also attributed the difference between dry weights of nodules obtained from plant inoculated with different rhizobia strain to the size of nodules produced.

3.3 Shoot dry weight (SDW) in gram per plant:

There was a significant different ($P<0.05$) between strain 2NAG9d and BR3267 (ref) but there was no different between the control and all the inoculated plants. Rhizobia strain 2NAG9d gave a higher mean value of 9.20g while strain BR3267(ref) gave the lowest mean value of 6.73g for SDW in gram per plant. The highest mean values were obtained from rhizobia strains 2NAG9d, $60kgha^{-1}$ treatment, 2NG5261, 2NG91awith mean values of 9.20g, 8.30g 8.21g and 8.05g respectively. Rhizobia strains 2NG53e, CB756(ref), BR3262(ref) and BR3267(ref) gave lowest shoot dry weight (SDW) than the un-inoculated that obtained mean value of 7.796g as shown in Table 2. Higher mean value obtained from plants treated with 2NAG9d, indicated percentage increase but was not significantly different from the control and the urea supplied plants. Aliyu *et al*. (2013)

attributed greater shoot biomass in inoculated plants than un-inoculated plants to high competition between native rhizobia population and the introduced rhizobia strains.

TABLE 2
EFFECT OF VARIOUS N SOURCES ON NUMBER OF NODULES, NODULES DRY WEIGHT AND SHOOT DRY WEIGHT

N Source	Nodule Number (Per plant)	Nodules dry Weight (g/pl^{-1})	Shoot dry weight (g/pl^{-1})
Control	14^{ab}	0.17^{a}	7.79^{ab}
$60kgha^{-1}$	9^{b}	0.14^{a}	8.30^{ab}
2NAG53e	11^{b}	0.28^{a}	7.20^{ab}
2NAG91a	13^{ab}	0.17^{a}	8.05^{ab}
2NAG9d	11^{b}	0.15^{a}	9.20^{a}
CB756(ref)	12^{ab}	0.16^{a}	7.08^{ab}
2NAG5261	17^{a}	0.22^{a}	8.21^{ab}
BR3262(ref)	14^{ab}	0.19^{a}	7.08^{ab}
BR3267(ref)	14^{ab}	0.19^{a}	6.73^{b}
SE±	1.99	0.06	0.84

Means with the same superscript are not significantly different

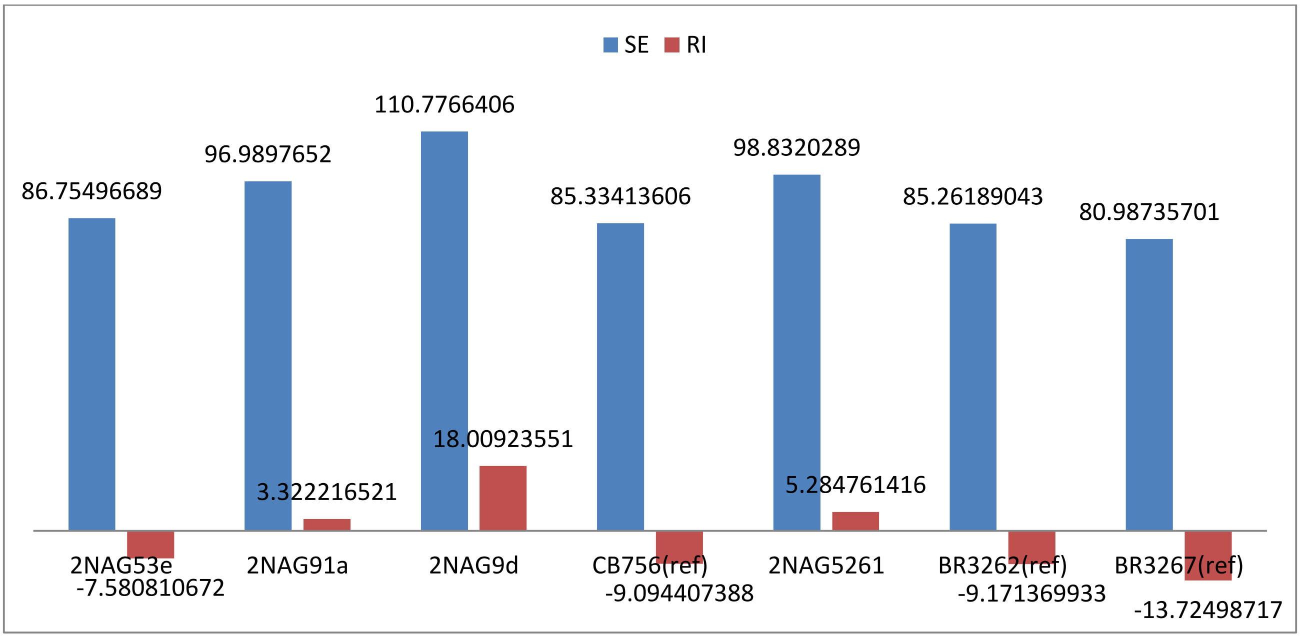

FIGURE 1: Shoot dry weight as a measure of Symbiotic Effectiveness (SE) of seven elite cowpea rhizobia and Response to Inoculation (RI)

3.4 Response to inoculation (RI) and Symbiotic effectiveness (SE) of shoot respectively:

Response to inoculation in IT99K-1-1 cowpea variety was highest in plants treated with 2NAG9d followed by 2NAG5261 and 2NAG91a inoculants with 18.00%, 5.28% and 3.32% respectively with no significant difference. Plants treated with 2NAG53e, CB756(ref), BR3262(ref) and BR3267(ref) inoculants had -7.58%, -9.09%, -9.17% and -13.72% respectively indicating a negative response to inoculation.

The symbiotic effectiveness (%SE) for the inoculants ranges from 80.98% to 110.99%. The plants treated with 2NAG9d had the highest percentage for symbiotic effectiveness followed by plants treated with 2NAG5261 and 2NAG91a rhizobial strains with 110.77%, 98.83% and 96.98% respectively as indicated in (figure1) Plants treated with 2NAG53e, CB756(ref), BR3262(ref) and BR3267(ref) inoculants had 86.75%, 85.33%, 85.26% and 80.98% respectively for symbiotic effectiveness.

Shoot dry weight is mostly considered to indirectly measure symbiotic effectiveness between legumes and the nitrogen fixing bacteria. Symbiotic effectiveness is also an important measure use in evaluating and determining strains for inoculants production and recommendation.

There was no significant difference in response to inoculation of cowpea variety IT99K-1-1 even though, highest values were observed in plants treated with 2NAG9d strain followed by plants treated with 2NAG5261 and 2NAG91a strains with 18%, 5.3% and 3.3% increased respectively as shown in figure 4.1. Plants treated with 2NAG53e, CB756(ref), BR3262(ref) and BR3267(ref) inoculants had -7.58%, -9.09%, -9.17% and -13.72% respectively which indicated a negative response to inoculation as shown in figure 1

Symbiotic effectiveness (SE) obtained from rhizobia strain 2NAG9d was 110.99% which was more than 100%, indicated that the shoot dry weight produced by plants treated with this strain was greater than that of urea supplied plants. This indicated that plants inoculated with this strain obtained more nitrogen than the urea applied plants. This also indicates the level of compatibility between the cowpea variety and the rhizobium strain. There was no response to inoculation at SE 86.75% but there was a proportional increase in response to inoculation from 96% to 110% (SE) This has shown that cowpea variety IT99K573-1-1 responded higher to 2NAG9d strain in terms of shoot biomass. This also means that symbiotic effectiveness of an inoculant has a direct relationship with response to inoculation provided all other environmental conditions and crop management practice are well checked. Low shoot biomass production in some of the inoculated cowpea plant compared to the control could also be a result of low nodule formation that reduced N_2 fixation and consequently reduced rapid plant growth and height. Low growth and shoot height as a result of low nodule formation was also observed by Peoples *et al.*(2001), Yoshioka and Maruyama (1990). Inoculation response was more significant in soils having lower indigenous rhizobia population and fertility (Imran *et al.,* 2015). Several reports by many authors observed that high population size of indigenous rhizobia is a major challenge for inoculant performance under field condition. (Jones *et al*., 1979; Dughri *et al*., 1983; Dudeja and Khurana 1988; Sheoran *et al*., 1997). To have successful inoculation with effective isolate that could result in an enhanced nodultion and growth most of these condition therefore must be in place. Number of available indigenous rhizobia may be insufficient to nodulate the host and the average effectiveness of the indigenous population in the soil has to be inadequate to support the host fixed nitrogen required (Bergersen, 1970). High shoot dry weight observed in 2NAG9d treatment could also be due to late maturity. According to Bidlack *et al*.(2007) late maturing variety accumulate more biomass in vegetative shoot component while early maturing varieties partitioned more photosynthate into reproductive structure.

TABLE 3
EFFECT OF N SOURCES (INOCULANTS) ON YIELD AND YIELD COMPONENTS OF COWPEA

N Sources	Pod load/plant	Pod yield ($kgha^{-1}$)	100 seed wt(g)	Grain yield ($kgha^{-1}$)
Control	4^{a}	769.44^{abc}	21.93^{a}	486.24^{abc}
$60kgNha^{-1}$	4^{a}	1067.22^{a}	21.83^{a}	643.49^{a}
2NAG53e	5^{a}	832.77^{abc}	21.20^{a}	505.52^{abc}
2NAG91a	5^{a}	878.88^{ab}	16.73^{a}	584.78^{ab}
2NAG9d	5^{a}	819.44^{abc}	17.43^{a}	474.98^{abc}
CB756(ref)	5^{a}	883.88^{ab}	21.19^{a}	630.99^{ab}
2NAG5261	4^{a}	538.33^{c}	17.15^{a}	327.62^{c}
BR3262	4^{a}	600.55^{bc}	17.70^{a}	395.78^{b}
BR3267	5^{a}	703.88^{bc}	16.57^{a}	452.74^{abc}
SE±	0.58	116.93	2.32	84.51

Means with the same superscript are not significantly different.

3.5 Effect of N sources on pod load per plant:

The highest number of pods per plant was obtained from CB756(ref), 2NAG91a, 2NAG53e, 2NAG9d and BR3267(ref) with mean values of 5, 5, 5, 5and 5 respectively as shown in (Table 3) while the lowest number of pods per plant was obtained from rhizobia strain 2NAG5261, control, $60kgNha^{-1}$ and BR3262(ref)with values of 4, 4, 4 and 4 respectively. Means of statistical analysis indicated that there was no significant difference (P<0.05) among all the treatments and the control. This is contrary to *Malik et al*. (2006), who reported that when cowpea is inoculated with rhizobia strain, it increase the number of pods per plant as a result of improve growth and high nitrogen nourishment from biological nitrogen fixation. This result is in agreement withYamur and Engin (2004) who reported that inoculation did not affect the number of pod per plant in cowpea

3.6 Effect of N sources on pod weight per kg/ha^{-1}:

The 60kgNha^{1} treatments, rhizobia strains CB756(ref), 2NAG91a 2NAG53e, and 2NAG9d gave the highest mean values of (1067.2kg, 883.9kg, 878.9kg, 832.8kg and 819.4kg) respectively which were more than the control that had a mean value of 769.4kg as shown in (Table 3). 2NAG5261, BR3262 and BR3267(ref) all had lower mean values compared to the control as shown in (Table 4.5) The 60kgNha^{1} applied plants had the highest percentage increase of 38.7% followed by CB756(ref) with 14.9%, 2NAG91a (14.2%) 2NAG53e (8.2%) and 2NAG9d(6.5%) for pod weight/kgha^{-1}. Statistically, there was no significant difference between the control and other treatments. This has proven that inoculation has no significant effect on pod weight. The non significant effect of inoculation could be due to as assumed by Kimiti and Odee (2010) that effective native rhizobia that nodulates cowpea was in abundance in tropical soils and therefore, inoculation was not necessary.

3.7 Effect of inoculation on 100 seed weight per grams among the treatments:

Statistically there was no significant difference (P<0.05) in all the treatments and the control. BR3267 treatment had the lowest one hundred seed weight as shown in table, but was not significantly different from all other treatments. This is contrary to the findings reported by Ali *et al*., (2004) and Kazemi *et al*., (2005) that inoculation with Bradyrhizobia significantly increased one hundred seed weight in legumes.

3.8 Effect of treatment on cowpea yield (Seed weight/kg/ha):

The nitrogen applied plants obtained the highest mean value of 643.49kgha^{-1}which is 32% increase in yield followed by CB756(ref) and 2NAG91awith mean values of 630.99kgha^{-1} (29.7%) increase, 584.78kgha^{-1}(20.3%)increase in yield respectively while 2NAG5261 had 327.62kgha^{-1} which showed no yield increase compare to the control as shown in table 3.

Statistically there was a significant difference (P<0.05) between the nitrogen applied plants and 2NAG5261, BR3267 treatments in terms of grain yield. However, statistically there was no significant difference in cowpea yield between the control that obtained a mean value of 486.24kgha^{-1} and all the inoculants and the nitrogen applied plants. Despite the inoculation of cowpea, the grain yield was not different from the average cowpea yield of 483kg/ha estimated by the food and agriculture organization (FAO) of the united nation. This proved that inoculation of cowpea with these rizobia strains had no effect on cowpea yield and productivity in the study area. This could be due to high population size of ineffective native rhizobia in the soils or the inability of the introduced strains to compete effectively. Based on the result from the sites of trial is obvious that the sites contain very numerous number of native rhizobia capable of modulating cowpea. It could also be that, the introduced Bradyrhizobia were yet to adapt to the new environment, since conditions in the laboratory where they produced and tested was different from the field conditions. The newly inoculated cells take a longer time adapting to the new environment to get use to the new medium (Soil) and the physical conditions and inducing the necessary enzymes for growth before it can compete at the host rhizoplane to occupy a significant proportion in the nodules. Deaker *et al.*, (2004) and Graham (2009) also observed and stated that introduced rhizobia population requires a time period to adapt to the environment and their population size can increase 100 times one year after introduction. In a study by Soares *et al*., (2006) inoculation increased cowpea grain yield from 341kgha^{-1} to 957kgha^{-1}. Also, Zilli *et al*., (2009) reported that inoculation increased cowpea yield from 955kgha^{-1} to 2334kgha^{-1}. In (2011) Costa *et al*., also proved that inoculation of cowpea with effective rhizobia strains increased cowpea yield from 955kgha^{-1} to 1223kgha^{-1}. Contrary to this research, the nitrogen applied plants and the rhizobia strains CB756(ref), 2NAG91a, 2NAG53e applied plants with mean values of 643.49kgha^{-1}, 630.99kgha^{-1}, 584.78kgha^{-1} and 505.52kgha^{-1} respectively as shown in (Table 4.5) obtained higher mean values but were not statistically significantly different from the control. This is also not in agreement with Ulzen *et al*., (2016) that observed significant increase in grain yield of cowpea after inoculation with Bradyrhizobia inoculants. Almeida *et al*., (2010) proved that the application of three inoculants strains separately increased cowpea grain yield by 29 to 50% compared to the uninoculated control. Nyoki and Ndakidemi (2013) attributed increased in grain yield of cowpea due to effectiveness of Bradyrhizobial inoculants in fixing the required nitrogen to meet the nutrient requirement for cowpea. Therefore, the trial of these inoculants contrary to other researches did not show any increase in grain yield of the cowpea variety IT99K-573-1-1 in Minna.

IV. CONCLUSION AND RECOMMENDATION

From the fertility and suitability rating the soil texture and soil pH was suitable for cowpea production and microbes responsible for nutrient cycling. However, each of the fields (replicates) has one or two limiting factor for cowpea production and need more nutrient elements like phosphorus which is very important in nitrogen fixation and absorption.

There was no effect of inoculation in number of nodules, though plants treated with 2NAG5261 had high number of nodules than the plants treated with 60KgNha-^{1} but could not translate in nodules dry weight and grain yield. Shoot dry weight which is mostly considered to indirectly measure symbiotic effectiveness, nitrogen fixation in legumes had shown no statistical difference in all treatments and showed no significant difference in response to inoculation. There was no response to inoculation in terms number of nodules, nodules dry weight, shoot dry weight, pod weight per plant, pod weight per kilogram per hectare, one hundred seed weight and total grain yield of IT99K-573-1-1 cowpea variety.

This work therefore recommends that further trial of these inoculants should be carried out on other varieties of cowpea and other legumes because different varieties may respond differently to each inoculant due to genetic make- up. The evaluation of the these inoculants should also be conducted in other places outside Minna in order to capture the differences that may exist in physical, chemical and biological properties of soils because inability of cowpea to respond to inoculation could be attributed not only to the crop variety but also environmental conditions and can be site specific.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Sociology of Health and the Environment: The Management of Infectious Medical Waste at the University Hospital (CHU) of Abidjan/Cocody, from Sorting to Incineration, Côte D'ivoire

Kobenan Yao Innocent[1*]; Sinan Adaman[2]

[*1]Doctoral Candidate, Environmental Sociology, Department of Sociology, UFR of Social Sciences, University Peleforo Gon Coulibaly of Korhogo (Côte d'Ivoire)

[2]Lecturer-Researcher, Department of Sociology, UFR of Social Sciences, University Peleforo Gon Coulibaly of Korhogo (Côte d'Ivoire)

*Corresponding Author

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Abstract— *This study aims to draw the attention of actors involved in the management of infectious medical waste to the potential risks posed to human health and the environment. Cocody University Hospital (CHU de Cocody), due to its central role in the healthcare system, was selected as the research site. To achieve the study's objectives, scientific literature and results from field surveys were mobilized. Our investigations show that the informal and inadequate management of hospital waste at the CHU of Cocody is strongly linked to the neglect of established standards issued by the Ministry of Health as well as socioeconomic constraints. Waste sorting, which should be performed at the source by healthcare staff, is frequently bypassed. This failure greatly complicates the management of infectious medical waste. The repeated breakdowns of the incinerator are largely due to improper sorting practices, resulting in some infectious waste being diverted to landfills. Such waste becomes a source of contamination for soil, air, and both surface and groundwater, posing serious risks to all individuals exposed to it. The research highlights how social actors develop strategies that operate outside formal norms to meet their own interests.*

Keywords— hospital waste, health policy, dysfunction.

I. INTRODUCTION

The Ivorian population, or more precisely the resident population as defined in the General Population and Housing Census (RGPH), increased from 6,709,600 inhabitants in 1975 to 29,389,150 inhabitants in 2021. This represents a significant demographic expansion over a span of fifty years. Regarding the use of healthcare services, the national rate of access to health facilities rose from 67% in 2016 to 70.17% in 2020. This increase, attributed to improved technical capacities in healthcare facilities, led to a higher number of patient visits. Combined with numerous health interventions, including vaccination campaigns, the result is a substantial rise in the production of medical waste.

The management of this waste—estimated at 25.55 tons of solid waste per day, or approximately 9,325.09 tons annually—is a major public health and environmental concern. Poor sorting practices persist, with 38% of public institutions failing to separate waste at the source. This elevates the proportion of infectious, sharp, and hazardous waste.

Healthcare facilities have recently benefited from rehabilitation and equipment upgrades through a large five-year program (2016–2020) implemented by the Government and its international partners. The Ivorian health system, like many others globally, is mixed and pluralistic, comprising both public and private actors. According to the 2020 National Health Statistical Survey (RASS), Côte d'Ivoire has 3,831 healthcare facilities, with 60% belonging to the public sector and 40% to the private sector.

The healthcare system is structured into three levels—primary, secondary, and tertiary—organized in a pyramidal form. Cocody University Hospital, a key component of the tertiary level, was chosen as the research site. This study aims to raise awareness among actors responsible for infectious medical waste management regarding the risks such waste poses to human health and the environment. Scientific literature and survey data were used to formulate recommendations.

II. BRIEF OVERVIEW OF THE IVORIAN HEALTH SYSTEM

The Ivorian healthcare system is organized into three levels:

2.1 Primary Level:

This level serves as the entry point into the health system. It includes facilities offering curative, preventive, educational, and promotional services. These include:

- Rural Dispensaries (DR)
- Rural Health Centers (CSR)
- Urban Health Centers (CSU)
- Specialized Urban Health Centers (CSUS)
- Urban Health Training Centers (FSU)

2.2 Secondary Level:

This level supports the primary level by providing enhanced diagnostic and treatment capacity. Facilities include:

- General Hospitals (GH)
- Regional Hospital Centers (RHC)
- Specialized Hospital Centers (SHC) without National Public Establishment (EPN) status

2.3 Tertiary Level:

This level provides specialized care and advanced diagnostic, treatment, training, and research capabilities. It includes:

- University Hospital Centers (CHU)
- Abidjan Cardiology Institute (ICA)
- Raoul Follereau Institute (IRFCI)
- National Public Hygiene Institute (INHP)
- National Blood Transfusion Center (CNTS)
- National Public Health Laboratory (LNSP)
- National Institute of Public Health (INSP)
- Alassane Ouattara National Oncology and Radiotherapy Center (CNRAO)
- Emergency Medical Assistance Service (SAMU)
- National Center for the Prevention and Treatment of Renal Failure (CNPTIR)

Cocody University Hospital, a major tertiary-level facility, was chosen for this study because of its high production of biomedical waste and its critical place in the national healthcare infrastructure.

III. NATIONAL AND INTERNATIONAL REGULATIONS

Multiple documents govern health and environmental policies in Côte d'Ivoire. Law No. 2023-900 of November 23, 2023 (Environmental Code) reinforces environmental protection for sustainable development and guarantees citizens an ecologically balanced living environment. The law applies to all forms of pollution and covers installations that may pose risks to public health, environmental quality, safety, or public order.

It prohibits:

- dumping, incineration, or discharge of harmful substances into maritime waters under Ivorian jurisdiction
- unauthorized importation or dumping of waste

- disposal of waste in lagoon, continental, or maritime waters

Decree No. 131/MSHP/CAB/DGHP/DRHP of June 3, 2009 regulates medical waste management. It classifies medical waste into three categories:

1. Category 1: household-like waste
2. Category 2: infectious medical waste
3. Category 3: non-infectious medical waste

Medical waste in Categories 2 and 3 must be treated primarily by incineration.

The 2009 National Policy on Injection Safety and Medical Waste Management reaffirms Côte d'Ivoire's commitment to ensuring injection safety and environmentally sound waste management in both public and private sectors. Solid waste must be incinerated or disposed of safely, and liquid waste must be treated before discharge.

IV. MATERIALS AND METHODS

4.1 Study Site:

The study was conducted in the Abidjan District, specifically at the Cocody University Hospital. Given its size and role, this facility is a major producer of biomedical waste.

4.2 Population:

The study population consists of:

- medical staff
- administrative staff
- technical staff involved in waste collection and disposal (SEQUOIA, NETSI)
- ELTSON incineration staff

4.3 Inclusion Criteria:

Individuals working in the hospital or in the companies SEQUOIA, NETSI, or ELTSON who were present during data collection.

4.4 Exclusion Criteria:

Eligible individuals absent during data collection.

4.5 Type of Study:

This is an exploratory and descriptive study aimed at identifying waste management problems at the CHU and proposing solutions. Both quantitative and qualitative variables were collected between December 4, 2024 and April 10, 2025.

4.6 Material:

Data were collected using:

- questionnaires with open and closed questions
- interview guides for qualitative input
- infographics
- covert and participant observation

4.7 Sample:

A random sampling method was used. Seventy-one (71) individuals participated in the survey.

TABLE 1
DISTRIBUTION OF RESPONDENTS BY DEPARTMENT

University Hospital Staff						Technical Maintenance Staff			
Administrative		Medical (A)		Medical (B)		SEQUOIA		NETSI	
V.A	V.R (%)	V.A	V.R (%)	V.A	V.R (%)	V.A	V.R (%)	V.A	V.R (%)
3	4.22%	11	15.49%	7	9.86%	20	28.17%	30	42.25%

(V.A) Absolute value ** (V.R) Relative value

V. RESULTS

The objective of this study is to contribute to improving the overall management of medical waste at the University Hospital Center (CHU) and, more broadly, to extend these recommendations to other healthcare establishments and related institutions in Côte d'Ivoire. To achieve this, the findings summarize and interpret the responses collected during our investigation.

5.1 Data Analysis and Interpretation:

5.1.1 Collection of Sharp, Cutting, and Piercing Objects (OPCT):

PHOTO 1: A safety box for sharp, cutting, and piercing objects (OCPT)

PHOTO 2: A full and overflowing safety box in the group emergency department

Source: Our investigation, 2024

Photo 1 presents the designated container used for sharp objects, including used syringes, scalpel blades, and intravenous needles. These containers are provided by the hygiene department, while private cleaning companies supply color-coded bags for overall waste management and handle their collection once full. Each waste type is assigned a disposal container at the point of generation and must be filled only up to three-quarters of its capacity, marked by a red line (see Photo 1).

However, observations at the CHU revealed that healthcare personnel frequently exceed the recommended fill level. Overfilling the sharps containers exposes waste handlers to significant risks. A syringe may fall during handling and cause accidental injury, as illustrated in Photo 2.

This concern was confirmed by Respondent #7, a maintenance and sanitation worker, who stated:

"Once, while collecting these sharps containers, a syringe fell on my foot, and I had to go see the referring doctor, who put me on antiretroviral therapy. Luckily for me, the syringe wasn't contaminated with HIV. Our work here is really complicated because the healthcare staff doesn't make it easy for us."

This testimony highlights the occupational hazards faced by personnel responsible for collecting and transporting sharps containers, particularly the risk of accidental needlestick injuries.

5.1.2 Collection of Soft Infectious Medical Waste (Excluding OPCT):

PHOTO 3: Failure to comply with source separation
Source: Our investigation, 2024

Photo 3 shows a complete IV set, including the fluid bag, tubing, and injection lines. This type of waste falls under the category of soft infectious medical waste and should therefore be disposed of exclusively in yellow bag-type containers. Despite the availability of appropriate yellow containers, healthcare staff were observed discarding such hazardous waste into black bag-type containers intended for household or similar waste.

This behavior indicates poor compliance with waste segregation guidelines and suggests a lack of enforcement. Respondents confirmed this through statements such as:

"When I'm working, I don't sort the waste because I don't have the time; the workload is too heavy." "Since I've been here, I only put sharp, cutting, and piercing objects in the safety containers; otherwise, everything else gets mixed in. There's no time for that."

This non-compliance poses serious risks. Workers transporting mixed waste can be exposed to needlestick injuries or other hazards due to improper segregation. One interviewed worker confirmed having suffered such an injury and receiving occupational health follow-up.

In summary, source separation of medical waste is not being respected. Hazardous infectious waste is often found in black bag containers and vice versa. Such practices increase the risk of injury and infection among waste handlers. These preventable incidents emphasize the need for strict adherence to proper waste segregation and packaging procedures.

5.2 Waste Quantification:

5.2.1 Waste Quantification and Analysis:

TABLE 2
FREQUENCY OF COLLECTION AND DISPOSAL OF INFECTIOUS WASTE

Activities	January to March	Satisfaction rate
Collections Household waste	Irregular	0.75
Destruction Infectious Waste	Regular	0.95

Source: Semi-annual activity report of the hygiene department, 2025

The table shows the frequency of household waste collection and infectious waste disposal at the CHU. Household waste is collected by the municipality, while infectious waste is incinerated by the service provider ELSTON at the CHU Cocody site.

During the three-month assessment period, significant challenges were identified. These included repeated breakdowns of the incinerator and delays by the municipal service in collecting household and similar waste, resulting in waste accumulation at the facility.

5.2.2 Waste Removal:

PHOTO 4: Temporary Waste Storage Area at the Cocody University Hospital
Source: Our investigation, 2024

The photograph shows the temporary waste storage area where all waste types are mixed together without separation. Proper storage requires designated compartments for each waste category to avoid contamination. At the entrance to this area, damaged safety containers and scattered syringes are visible, creating a hazardous environment for workers handling the waste.

This accumulation is primarily caused by repeated incinerator breakdowns and the municipality's failure to collect household and similar waste on schedule. The absence of proper waste sorting at earlier stages exacerbates the contamination and operational challenges.

According to an incinerator worker with 20 years of experience:

"We destroy what we can; the rest goes to the landfill because we have no choice. The repeated breakdowns of the incinerators and the healthcare staff's failure to sort waste make incineration very complicated, and the volume of infectious waste is increasing. So, Mr. Boss, we do what we can."

This statement confirms that some infectious waste ends up in public landfills—a violation of waste management regulations—due to equipment failures and inadequate sorting of waste at the source.

5.3 Obstacles Related to Waste Removal:

5.3.1 Organizational Constraints:

Waste removal at the facility occurs in two stages:

1. Transport from hospital services to the central landfill (incineration site)
2. Transport from the incineration site to the municipal public landfill for household and similar waste

Multiple obstacles arise during both stages. During internal transport, the lack of adequate garbage bags hinders proper packaging. Poor source segregation exposes sanitation workers to bloodborne infection risks. The shortage of appropriate transport containers forces some workers to carry waste manually, increasing their risk of needlestick injuries. Additionally, inconsistent collection schedules disrupt hospital services.

During external transport, only household and similar waste should reach the public landfill. However, due to improper segregation, infectious waste is mixed with non-infectious waste at the dump and transported together. Repeated incinerator breakdowns worsen this issue by leaving untreated infectious waste that must be relocated.

5.3.2 Economic Constraints:

The budget allocated for waste collection is 1,600,000 CFA francs per month, while the operational budget for the hospital remains fixed at 1,100,000 CFA francs per month. The expansion of the hospital—particularly the construction of the pediatric gynecology-obstetrics unit in 2023—has increased the volume of waste produced.

This additional waste load contributes to frequent incinerator breakdowns, and insufficient funding prevents timely repairs. The high cost of approved waste management equipment (containers, carts, and dedicated transport vehicles) also leads some service providers to disregard required standards.

5.3.3 Material Constraints:

At the Cocody University Hospital, waste is typically removed from the landfill area using wheeled bins or carts. However, frequent equipment failures often force workers to transport waste manually. Furthermore, the lack of adequate personal protective equipment (PPE) increases their vulnerability to needlestick injuries and respiratory infections.

VI. CONCLUSION

The management of infectious medical waste is an essential component of healthcare activities within all health facilities. Despite its importance, it continues to represent a major public health concern. Medical waste management, particularly at the Cocody University Hospital, remains a significant challenge that requires urgent attention and sustained corrective action.

The government has undertaken several initiatives aimed at improving waste management practices. These include training specialists in the field, integrating medical waste management modules into the university curriculum for medical and paramedical students, and organizing workshops and awareness programs. Additionally, regulatory frameworks, codes of practice, and the National Plan for the Management of Medical Waste (PNDGS) have been introduced to guide healthcare institutions in adopting appropriate procedures.

However, despite these efforts, the management of infectious medical waste in healthcare facilities—and especially at the Cocody University Hospital—remains inadequate. Observations from this study indicate that waste is not being handled in accordance with established standards. This highlights the need for stronger monitoring systems, improved infrastructure, enhanced staff training, and stricter enforcement of regulations to ensure safe, effective, and compliant waste management practices.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Morphometric and Macroanatomic Examination of Cavum Nasi in Kivircik Sheep: A Statistical Comparison by Gender

Yasin Baykalir[1*]; Zekeriya Ozudogru[2]; Busra Sonmez[3]

[*1]Department of Biostatistics, Faculty of Veterinary Medicine, Balikesir University, Turkey
[2,3]Department of Anatomy, Faculty of Veterinary Medicine, Balikesir University, Turkey
*Corresponding Author

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Abstract— *The nasal cavity of sheep exhibits complex anatomical structures that are important for respiratory function and breed-specific adaptations. Understanding its macroanatomical and morphometric characteristics can provide insights into species-specific traits. This study aims to determine the macroanatomical and morphometric values of certain structures within the nasal cavity of Kivircik sheep. Ten Kivircik sheep heads (5 males, 5 females) were used. Eighteen tissues of the cavum nasi (nasal cavity) and nasus externus were evaluated for length and thickness using a digital caliper. Data were analyzed using multi-factor and interactive analysis of variance (Two-Way ANOVA), the Mann-Whitney U test, and the Pearson correlation test. A positive and significant correlation was found between the length of the widest part of the concha nasalis dorsalis and the length of the plica basalis ($r = 0.661$, $p < 0.01$). Additionally, a positive and significant correlation was observed between the cranio-caudal length of the concha nasalis media and the width of its caudal end ($r = 0.510$, $p < 0.05$). The morphometric characteristics of the concha nasalis sections are largely symmetrical and independent of sex, with only minor biological variation in certain measurements.*

Keywords— Sheep, Nasal Cavity, Anatomical Structures, Morphometric.

I. INTRODUCTION

Sheep, from which people benefit for their meat, milk, skin, and wool, are among the first domesticated animal species. Sheep breeding has an important share in agricultural activities in most countries. In addition to the fact that most countries's climatic characteristics, land structure, and natural pastures are suitable for sheep breeding, sheep breeding is widely practiced due to its versatile productivity [1]. Kivircik sheep is one of the sheep breeds raised in Turkey, Bulgaria, and Greece. Kivircik sheep are mostly used for their meat yield. Their bodies are covered with white, coarse-mixed wool. Black and brown ones are also seen and are bred in Bulgaria. Males have white spiral horns, females have no horns. Head, neck, underbelly, and legs are naked. The head is long, the ears are short, the neck is long and narrow, the body is long and narrow, the rump is low and narrow, legs are long. The tail is long and thin and extends to the tarsus joint. The body is medium-sized. The fleece is carpet-like fleece and one of higher quality than the fleece of other local breeds. The Kivircik sheep ranks first among Turkish sheep breeds in terms of meat quality. The cranium in the axial skeleton system is located at the front of the skeletal system. It is a solid structure consisting mostly of double bones. The skull bones are divided into sections and examined separately according to the spaces they surround and the structures they form the basis of. These sections are called ossa cranii and ossa faciei. The facial part of the cranium forms the wall of the nasal cavity, called the cavum nasi, and the bony roof of the oral cavity. The cavum nasi (nasal cavity) forms the facial part of the respiratory system. The nasal cavity is a cavity divided into two halves by a partition called the septum nasi. It opens into the nares in the front and the choana in the back and the pars nasali pharyngis. It has a roof, a floor, and two lateral walls, one inner and one outer. The nasal cavity is divided into the airways called the meatus nasi dorsalis, meatus nasi medius, meatus nasi ventralis and meatus nasi communis through the conchae [2,3]. The cranial bones encase and protect the brain and are meticulously categorized into the calvaria and the skull base. The calvaria, or skullcap, consists of the frontal, parietal, and occipital bones, each contributing to the overall shape and integrity of the cranial vault. In contrast, the base of the skull encompasses the sphenoid, temporal, and ethmoid bones, which articulate to form the complex floor that supports vital neurovascular structures [4].

In addition to their protective roles, these bones provide crucial attachment points for muscles involved in mastication and head movement. The intricate sutures that connect them allow for flexibility during growth and development, while also serving as landmarks for both anatomical study and surgical intervention [5]. Meanwhile, the facial bones contribute to the structural framework of the face, housing the nasal cavity, orbits, and dental arches. Comprising the maxillae, zygomatic bones, nasal bones, and mandible, these elements support the overlying soft tissues and play a pivotal role in functions such as respiration, mastication, and articulation [6,7]. Each bone's unique morphology is tailored to its function, with foramina facilitating the passage of nerves vessels, and sinuses providing resonance to the voice while reducing overall skull weight. The intricate interplay between these elements underscores the skeleton's dual role as both a protective encasement and a dynamic framework for the human body. Thus, a comprehensive understanding of skull anatomy is essential for both anatomical knowledge and clinical practice [8]. The aim of this study is to reveal the macro-anatomical and morphometric characteristics of certain structures of the nasal cavity in Kivircik sheep. In addition, statistical evaluations of the morphometric and macro-anatomical features of the cavum nasi were conducted.

II. MATERIAL AND METHODS

Ethics approval was not required for this study because all materials used were obtained from slaughterhouse by-products. A priori power analysis was conducted to evaluate the adequacy of the sample size for two-way ANOVA and correlation tests. With a total sample size of 10 sheep (5 males, 5 females), the achieved power was sufficient only to detect large effect sizes (Cohen's $f > 0.40$ for ANOVA; $r > 0.80$ for correlation) at $\alpha = 0.05$. Therefore, the study was adequately powered for large effects, but underpowered for detecting small-to-moderate effects. In this study, the formations in the nose and nasal cavity of 10 Kivircik sheep (5 males, 5 females) were examined macroanatomically and morphometrically. For this purpose, Kivircik sheep brought to the Meat Integrated Facility for slaughter were used in Turkey, Balikesir province. The heads were brought to Balikesir University, Faculty of Veterinary Medicine, Anatomy Laboratory. After the heads were weighed as a whole, measurements were taken of the external noses of the heads. Then, using a hand saw, these heads were separated into two equal halves in the sagittal direction from the right median line in order not to damage the nasal septum. Measurements of each head-half and measurements of the septum nasi were made. A total of 18 measurement points were determined. Measurements were made with the aid of a digital caliper. The other two heads were photographed transversely, first from the rostral third level of the dental pad, then from the level of the caudal edge of the first premolars, then from the level of the caudal edge of the third premolars, and finally from the level of the caudal edge of the first molars.

All measured points are named and coded with letters as follows:

Measurement points of the external nose

A. Nostril length

B. Distance between two nostrils

C. Distance from the nostril to the upper lip

Measurement points of concha nasalis dorsalis

D. Cranio-caudal length of concha nasalis dorsalis

E. Distance of cranial tip to palatum durum

F. Distance of caudal tip to palatum durum

G. Widest point of concha nasalis dorsalis

Measurement points of concha nasalis media

H. Cranio-caudal length of concha nasalis media

I. Distance of cranial tip to palatum durum

J. Width of caudal tip

K. Widest point of concha nasalis dorsalis

Measurement points of concha nasalis ventralis

L. Cranio-caudal length of concha nasalis ventralis

M. Distance of cranial tip to palatum durum

N. Widest point of concha nasalis ventralis

O. Length of Plica alaris

P. Length of Plica basalis

Measurement points of septum nasi

R. Septum nasi length

S. Septum nasi thickness

2.1 Statistical analyses

Analyses were performed using the IBM®SPSS 22 package program. Whether there was a statistical difference between the data of the measurements of the right and left sides of the anatomical structure with gender and whether gender and organs being right or left affected each other and whether there was an interaction between them was examined using the multi-factor and interactive analysis of variance (Two-Way ANOVA) test. At the same time, effect sizes related to gender and organs being right or left were also calculated. The existence of a statistically significant relationship between all examined features (lengths and thicknesses) was examined using the Pearson correlation test. Distance between two nostrils, Septum nasi thickness, and Septum nasi length was compared only on gender basis with Mann Whitney U test because data was not distributed normally. Statistical significance was accepted when $p \leq 0.05$ [9].

III. RESULT AND DISCUSSION

Examination of the parameters of the concha nasalis dorsalis is presented in Table 1. The measurements of the concha nasalis dorsalis did not show significant differences between sexes or sides. Although slight variations were observed between males and females and between the right and left sides for all measured traits, these differences were not statistically significant ($p > 0.05$). Additionally, the interaction between gender and side had no significant effect on the measured values. Effect sizes were very small, indicating minimal practical impact of gender, side, or their interaction on the anatomical dimensions of the concha nasalis dorsalis.

TABLE 1
EXAMINATION OF THE PARAMETERS OF THE CONCHA NASALIS DORSALIS USING MULTI-FACTOR AND INTERACTIVE ANALYSIS OF VARIANCE

		Concha nasalis dorsalis			
		D	**E**	**F**	**G**
Gender	Male	112.69±2.24	28.80±1.05	54.21±1.21	13.63±0.75
	Female	112.09±0.97	27.91±0.68	54.47±1.11	12.61±0.29
Side	Right	111.99±2.97	28.62±0.82	53.83±0.84	13.02±0.69
	Left	112.79±3.78	28.08±0.63	54.85±1.38	13.22±0.54
Gender*Side	Male-Right	111.98±1.60	29.27±1.36	53.85±1.34	13.65±0.81
	Male-Left	113.40±1.84	28.32±0.83	54.57±2.23	13.62±0.80
	Female-Right	112.00±1.79	27.97±1.03	53.82±2.23	12.40±1.15
	Female-Left	112.18±1.08	27.85±1.06	55.12±1.99	12.82±0.79
P-values	Gender	0.823	0.429	0.883	0.28
	Side	0.766	0.629	0.574	0.829
	Gender*Side	0.816	0.711	0.872	0.808
Effect size	Gender	0.004	0.053	0.002	0.096
	Side	0.008	0.02	0.027	0.004
	Gender*Side	0.005	0.012	0.002	0.005

Data are presented as Mean±Standard error. D: Cranio caudal length (mm) E: Distance of cranial tip to palatum durum (mm). F: Distance of caudal tip to palatum durum (mm). G: Widest point (mm)

The results of the multifactorial analysis of variance for the concha nasalis media are presented in Table 2. No statistically significant differences were observed between males and females for any of the evaluated parameters ($p > 0.05$). Similarly, no significant asymmetry was detected between the right and left sides ($p > 0.05$). Although the interaction between gender and side was also not significant (p > 0.05), effect size values indicated relatively higher variation for cranio-caudal length and caudal tip width.

TABLE 2
EXAMINATION OF THE PARAMETERS OF THE CONCHA NASALIS MEDIA USING MULTI-FACTOR AND INTERACTIVE ANALYSIS OF VARIANCE

		Concha nasalis media			
		H	**I**	**J**	**K**
Gender	Male	54.51±0.93	33.33±0.97	24.68±0.37	27.80±0.60
	Female	52.58±0.91	32.85±0.67	24.93±0.22	27.23±0.26
Side	Right	53.32±0.58	33.37±0.79	24.57±0.27	27.48±0.53
	Left	53.77±1.27	32.81±0.87	25.05±0.32	27.55±0.41
Gender*Side	Male-Right	53.42±0.35	33.87±1.28	24.17±0.28	27.60±1.03
	Male-Left	55.60±1.77	32.80±1.61	25.20±0.64	28.00±0.79
	Female-Right	53.22±1.20	32.87±1.06	24.97±0.41	27.37±0.52
	Female-Left	51.95±1.48	32.82±0.97	24.90±0.24	27.10±0.20
P-values	Gender	0.169	0.706	0.569	0.444
	Side	0.738	0.663	0.287	0.931
	Gender*Side	0.214	0.692	0.222	0.644
Effect size	Gender	0.151	0.012	0.028	0.05
	Side	0.01	0.016	0.094	0.001
	Gender*Side	0.125	0.014	0.122	0.018

Data are presented as Mean±Standard error. H: Cranio caudal length (mm). I: Distance of cranial tip to palatum durum (mm). J: Width of caudal tip (mm). K: Widest point (mm)

The results of the multifactorial analysis of variance for the concha nasalis ventralis are shown in Table 3. No statistically significant differences were observed between sexes for cranio-caudal length and widest point (p > 0.05). However, distance of the cranial tip to the palatum durum showed a near-significant difference between males and females (p > 0.05), with females presenting slightly higher values. Regarding the side factor, no significant differences were found (p > 0.05), although the effect size for widest point was relatively higher, suggesting a tendency for larger values on the left side. The interaction between gender and side was not significant (p > 0.05); nevertheless, moderate effect sizes were noted for widest point, mainly due to higher values observed in the female–left combination. The effects of gender, side, and their interaction on nostril length, the distance from the nostril to the upper lip, and the lengths of plica alaris and plica basalis were analyzed.

TABLE 3
EXAMINATION OF THE PARAMETERS OF THE CONCHA NASALIS VENTRALIS USING MULTI-FACTOR AND INTERACTIVE ANALYSIS OF VARIANCE

		Concha nasalis ventralis		
		L	**M**	**N**
Gender	Male	71.82±0.74	12.08±0.27	30.36±0.56
	Female	69.68±1.06	12.85±0.19	30.96±0.78
Side	Right	71.35±1.01	12.51±0.29	30.01±0.50
	Left	70.16±0.93	12.42±0.26	31.31±0.75
Gender*Side	Male-Right	72.90±0.64	12.00±0.40	30.25±0.79
	Male-Left	70.75±1.17	12.17±0.42	30.47±0.90
	Female-Right	69.80±1.67	13.02±0.23	29.77±0.70
	Female-Left	69.57±1.57	12.67±0.31	32.15±1.18
P-values	Gender	0.134	0.053	0.524
	Side	0.389	0.809	0.181
	Gender*Side	0.483	0.474	0.263
Effect size	Gender	0.177	0.278	0.035
	Side	0.062	0.005	0.144
	Gender*Side	0.042	0.044	0.103

Data are presented as Mean±Standard error. L: Cranio caudal length (mm). M: Distance of cranial tip to palatum durum (mm). N: Widest point (mm)

The mean values, standard errors, p-values, and effect sizes are summarized in Table 4. The comparison of morphometric parameters of the nasus externus and cavum nasi according to gender, side, and their interaction revealed that there were no statistically significant differences in any of the examined traits ($p > 0.05$). Although not significant, males tended to have a slightly longer plica alaris and plica basalis compared to females, while females showed marginally greater nostril length values. The effect size values indicated that gender had a small to moderate effect particularly on the length of the plica basalis, whereas all other parameters were influenced only minimally by gender or side. Side (right vs. left) and the interaction of gender*side showed negligible effects on all measured traits.

TABLE 4
INVESTIGATION OF SOME PARAMETERS OF NASUS EXTERNUS AND CAVUM NASI USING MULTI-FACTOR AND INTERACTIVE ANALYSIS OF VARIANCE

		Nostril length (mm)	The distance from the nostril to the upper lip (mm)	The length of Plica alaris (mm)	The length of Plica basalis (mm)
Gender	Male	21.93±0.67	15.43±0.42	104.63±1.95	95.18±1.50
	Female	22.78±0.84	15.52±0.31	101.72±0.76	91.53±0.81
Side	Right	22.55±0.84	15.65±0.43	102.72±1.37	93.46±1.37
	Left	22.17±0.70	15.31±0.32	103.63±1.75	93.26±1.40
Gender*Side	Male-Right	22.27±1.09	15.70±0.76	104.30±2.32	95.42±2.14
	Male-Left	21.60±0.89	15.17±0.47	104.97±3.50	94.95±2.41
	Female-Right	22.82±1.44	15.60±0.53	101.15±1.30	91.50±1.30
	Female-Left	22.75±1.12	15.45±0.52	102.30±0.90	91.57±1.18
P-values	Gender	0.477	0.883	0.219	0.071
	Side	0.751	0.574	0.692	0.915
	Gender*Side	0.88	0.754	0.918	0.884
Effect size	Gender	0.043	0.002	0.123	0.247
	Side	0.009	0.027	0.014	0.001
	Gender*Side	0.006	0.009	0.001	0.002

Data are presented as Mean±Standard error

The measurements of the nasus externus and cavum nasi, including the distance between two nostrils, septum nasi thickness, and septum nasi length, are summarized in Table 5. The comparison of the distance between two nostrils, septum nasi thickness, and septum nasi length according to gender revealed no statistically significant differences between males and females ($p > 0.05$). Although not significant, females exhibited slightly higher mean values for all measured parameters compared to males. The greatest numerical difference was observed in the distance between the two nostrils, while septum nasi thickness and length showed minimal variation between genders.

TABLE 5
EXAMINATION OF SOME PARAMETERS OF NASUS EXTERNUS AND CAVUM NASI

		Distance between two nostrils (mm)	Septum nasi thickness (mm)	Septum nasi length (mm)
Gender	Male	7.73±0.51	6.40±0.44	130.03±4.67
	Female	8.38±0.06	6.53±0.18	131.63±1.19
	P-values	0.102	0.663	0.564

Data are presented as Mean±Standard error

Correlation coefficients for the examined features are presented in Table 6. A positive and statistically significant correlation was determined between the cranio-caudal length of the concha nasalis dorsalis and the distance of the cranial end of the concha nasalis dorsalis to the palatum, and between the distance of the caudal end of the concha nasalis dorsalis to the palatum and the cranio-caudal length of the concha nasalis ventralis ($r = 0.696$, $p < 0.01$). A significant and positive correlation was found between the cranio-caudal length of the concha nasalis dorsalis and the length of the plica alaris ($r = 0.568$) and plica basalis ($r = 0.536$, $p < 0.05$). A positive and significant correlation was found between the distance of the cranial end of the concha nasalis dorsalis to the palatum durum and the length of the widest part of the concha nasalis dorsalis ($r = 0.502$, $p < 0.05$), the distance of the nostrils to the upper lip ($r = 0.650$, $p < 0.01$) and the length of the plica basalis ($r = 0.760$, $p < 0.01$); between the distance of the caudal end of the concha nasalis dorsalis to the palatum durum and the length of the nostril ($r = 0.648$, $p < 0.01$) and the length of the nasal septum ($r = 0.712$, $p < 0.05$). A positive and significant correlation was found between the length of the widest part of the dorsalis concha and the length of the basal plica ($r = 0.661$, $p < 0.01$). A positive and significant correlation was also found between the cranio-caudal length of the nasal concha and the width of the caudal end of the nasal concha ($r = 0.510$, $p < 0.05$). A high level of correlation was found between the thickness of the nasal septum and the distance from the cranial end of the nasal concha to the palatum ($r = 0.806$, $p < 0.05$). A positive and significant correlation was observed between the width of the caudal end of the nasal concha and the length of the widest part of the nasal concha ($r=0.640$) and the distance from the ventral concha to the palatum ($r = 0.658$, $p < 0.01$). A positive and significant relationship was found between the length of the widest part of the concha nasalis media and the distance between the two nostrils ($r = 0.763$, $p < 0.05$), plica alaris ($r = 0.572$, $p < 0.05$) and basalis length ($r = 0.638$, $p < 0.01$). Similarly, a positive and significant correlation was determined between the cranio-caudal length of the ventral concha nasalis and the length of the plica basalis ($r = 0.517$, $p < 0.05$). A positive and significant correlation was determined between the distance of the ventral concha nasalis to the palatum and the distances of the nostrils to the upper lip ($r = 0.555$, $p < 0.05$). The relationship between the length of the plica alaris and the length of the plica basalis was observed to be highly and statistically significant ($r = 0.849$, $p < 0.001$). A negative significant correlation was observed between the length of the nasal septum and the distance of the cranial end of the nasal concha to the palatum ($r = -0.710$) and the thickness of the nasal septum ($r = -0.748$, $p < 0.05$). A negative significant correlation was also found between the cranio-caudal length of the concha nasalis dorsalis and the distance of the cranial end of the concha nasalis media to the palatum durum ($p < 0.05$). No statistically significant correlation was observed for the remaining characteristics ($p > 0.05$).

The measurement points determined on the concha nasalis dorsalis and their distances are presented in Figure 1. The measurement points determined on the concha nasalis media and the measured distances are presented in Figure 2. The measurement points defined on the concha nasalis ventralis and their distances are presented in Figure 3. The measurement points and locations of the plica alaris and plica basalis are shown in Figure 4. The nostril length measurement point is shown in Figure 5. The distance between the nostril and the upper lip and the distance between the two nostrils are presented in Figure 6. The cavum nasi section taken from the third level of the dental pad and the location of the septum nasi, nasal cavity floor and dental pad are presented in Figure 7. The anatomical structures related to the section of the nasal cavity taken at the level of the caudal edge of the first premolar teeth are presented in Figure 8. The nasal cavity section taken from the level of the caudal edge of the third premolar teeth and the anatomical structures seen at this level are presented in Figure 9. The anatomical structures related to the nasal cavity section taken from the level of the caudal edge of the first molar teeth are presented in Figure 10.

TABLE 6
PEARSON CORRELATION COEFFICIENTS OF DATA FROM NASUS EXTERNUS AND CAVUM NASI

	E	F	G	H	I	J	K	L	M	N	A	B	C	S	R	O	P
D	0.43	0.696**	0.314	0.191	-0.549*	0.205	0.145	0.049	0.294	0.149	0.303	-0.034	0.064	-0.535	0.579	0.568*	0.536*
E		0.394	0.502*	0.378	0.123	0.393	0.510*	0.696**	0.489	0.072	0.25	0.426	0.650**	-0.028	0.329	0.476	0.760**
F			0.303	0.055	-0.547	-0.128	-0.106	0.243	0.241	-0.12	0.648**	-0.046	-0.247	-0.367	0.712*	0.424	0.418
G				-0.25	0.042	-0.005	0.286	0.301	-0.229	-0.04	-0.187	0.171	-0.04	-0.204	0.312	0.422	0.661**
H					0.048	0.510*	0.303	0.468	0.411	-0.04	0.11	-0.046	0.478	0.17	-0.206	0.269	0.272
I						0.344	0.244	0.392	0.01	0.011	-0.32	-0.083	-0.08	0.806*	-0.710*	0.058	0.087
J							0.640**	0.093	0.658**	0.469	-0.237	0.686	0.251	0.171	0.09	0.362	0.325
K								0.212	0.26	0.47	-0.495	0.763*	0.371	-0.259	0.27	0.572*	0.638**
L									0.154	-0.34	0.335	-0.071	0.483	0.156	-0.085	0.404	0.517*
M										0.227	0.37	0.531	0.555*	0.134	0.402	0.117	0.111
N											-0.301	0.548	0.226	0.055	0.026	0.103	0.131
A												-0.15	0.35	0.142	0.234	-0.085	-0.081
B													0.591	-0.235	0.391	0.153	0.306
C														0.079	0.163	-0.009	0.251
S															-0.748*	-0.621	-0.305
R																0.534	0.382
O																	0.849***

***: Statistical significance at P<0.05 level, **: Statistical significance at P<0.01, ***: Statistical significance at P<0.001.**
All letters are defined at Materials and Methods section

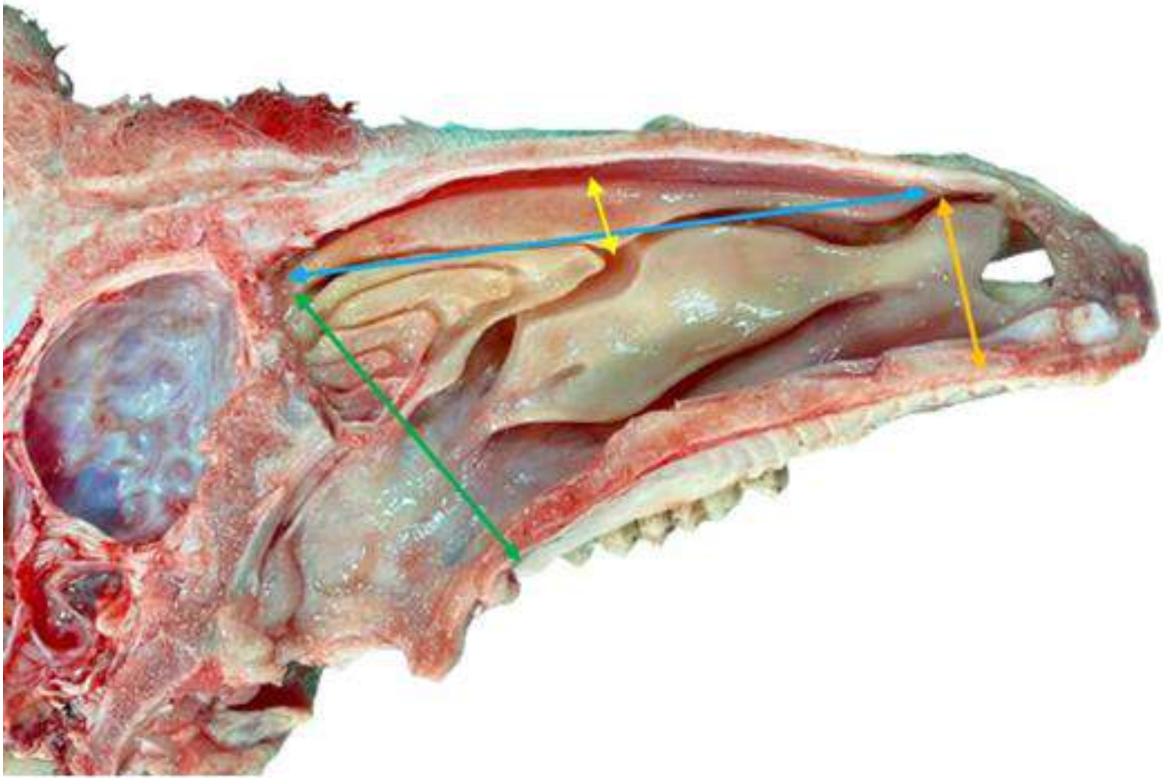

FIGURE 1. Measurement points of concha nasalis dorsalis (Original). Blue arrow: Cranio-caudal length of concha nasalis dorsalis (D), Orange arrow: Distance of cranial tip to palatum durum (E), Green arrow: Distance of caudal tip to palatum durum (F), Yellow arrow: Widest point of concha nasalis dorsalis (G)

In this study, the nasal and nasal cavum structures of Kivircik sheep were evaluated macroanatomically and morphometrically, and the obtained data were compared with those of other species and breeds. The nasal planum was found to be black, keratinized, and hairless, a finding consistent with results reported in Bengal goats and Garole sheep [10]. It was determined that the nasal cavity is divided into two equal halves by the nasal septum, and that this space contains three conchae (dorsalis, ventralis, and medialis) and four meati (dorsalis, medius, ventralis, and communis). This structure is consistent with the morphological order previously reported in the literature in different species [10–12]. Regarding nostril lengths, the values measured in Kivircik sheep (21.93±0.67 mm in males and 22.78±0.84 mm in females) were lower than those reported in Gaddi sheep and Egyptian goats [13,14]. This difference may reflect morphological diversity and environmental adaptations among the breeds. Similarly, the internostril distance was observed to be shorter in Kivircik sheep than in Egyptian goats and closer than in Egyptian Baladi dogs. The length of the nasal concha dorsalis was found to be longer in both males and females of Kivircik sheep compared to Egyptian goats and similar to the values reported in Gaddi sheep. Width measurements were also found to be shorter than in Gaddi sheep. The length of the nasal concha media in Kıvırcık sheep is quite consistent with the values reported in Egyptian goats and Gaddi sheep. The ventral concha nasalis is divided into plica alaris and plica basalis, similar to those in Yankasa sheep, Gaddi sheep, and camels. However, length values showed significant differences among species [13–15]. These variations are thought to be related to adaptation to different climatic conditions, respiratory functions, and the ecological niche of the species. Statistical analyses conducted in the study determined that gender and right-left lateralization factors did not influence each other in organ measurements. However, correlation analyses revealed significant relationships between some morphometric parameters. This suggests that the nose and navicular structures are developmentally and functionally interconnected. The morphometric data obtained from Kivircik sheep show both similarities to other small ruminants reported in the literature and also contain significant differences. These observed differences may represent the breed's unique morphological characteristics and its adaptations to environmental conditions. The morphometric characteristics of the concha nasalis sections are largely symmetrical and independent of sex, with only minor biological variation in certain measurements.

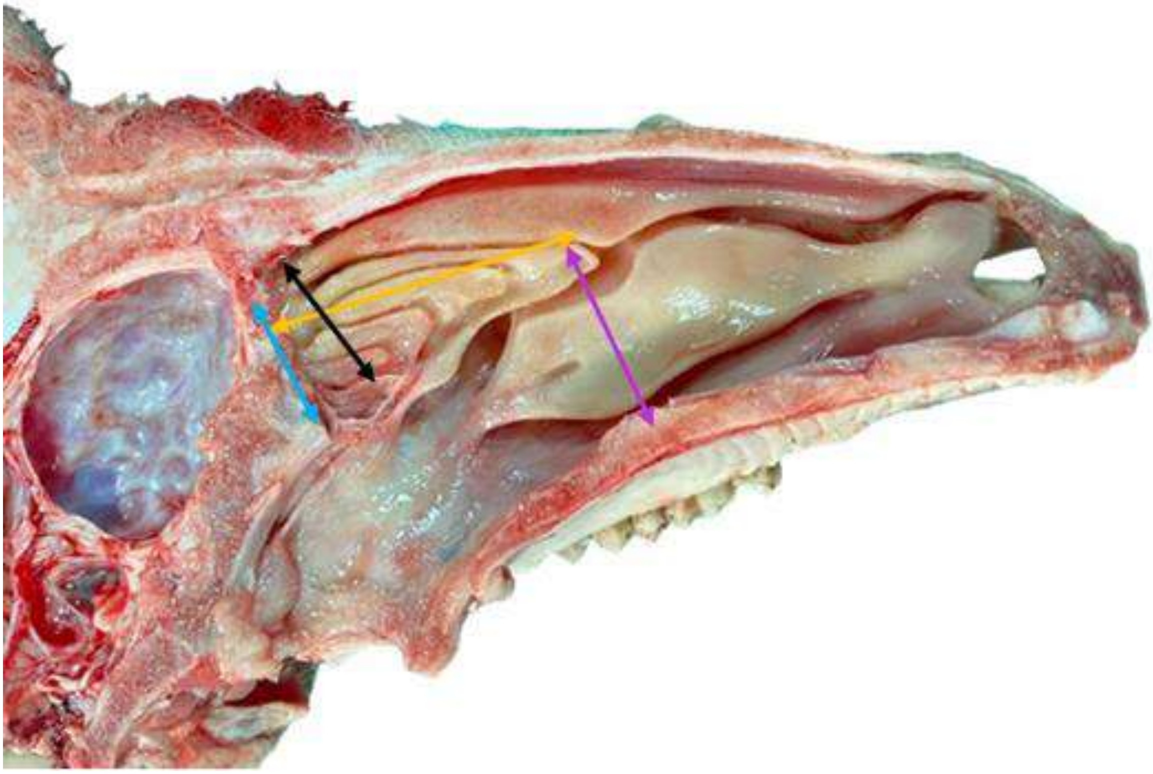

FIGURE 2: Measurement points of concha nasalis media (Original). Orange arrow: Cranio-caudal length of concha nasalis media (H), Purple arrow: Distance of cranial tip to palatum durum (I), Blue arrow: Width of caudal tip (J), Black arrow: Widest point of concha nasalis media (K)

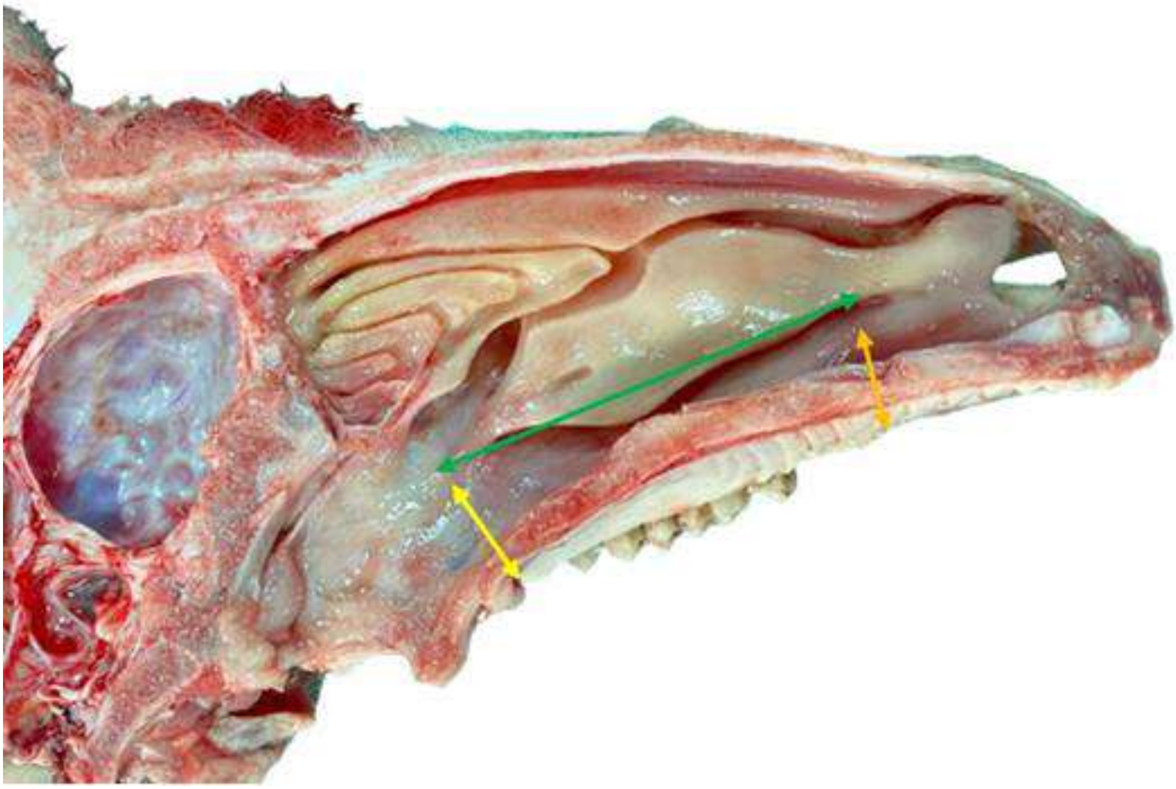

FIGURE 3: Measurement points of concha nasalis ventralis (Original). Green arrow: Cranio-caudal length of concha nasalis ventralis (L), Orange arrow: Distance of cranial tip to palatum durum (M), Yellow arrow: Widest point of concha nasalis ventralis (N)

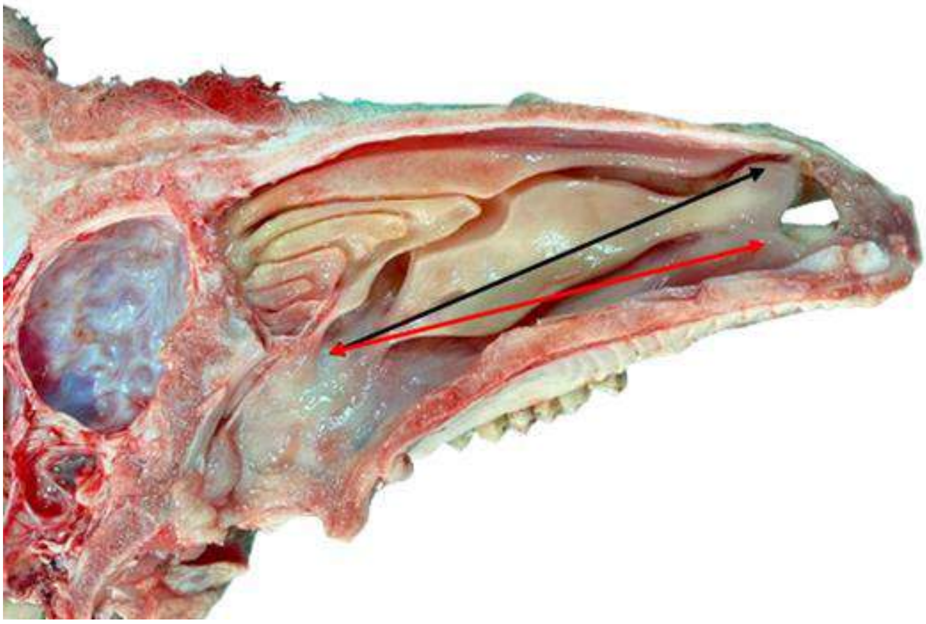

FIGURE 4: Measurement points of plica alaris and basalis (Original). Black arrow: Length of plica alaris, Red arrow: Plica basalis

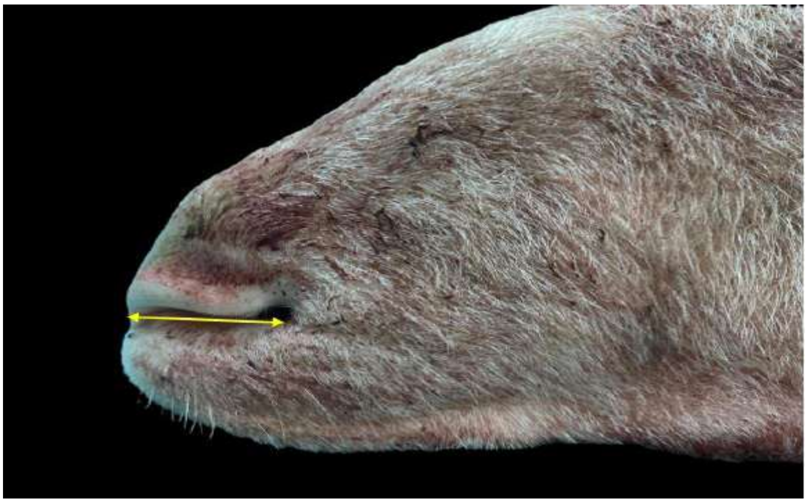

FIGURE 5: Yellow arrow: Nostril length (Original)

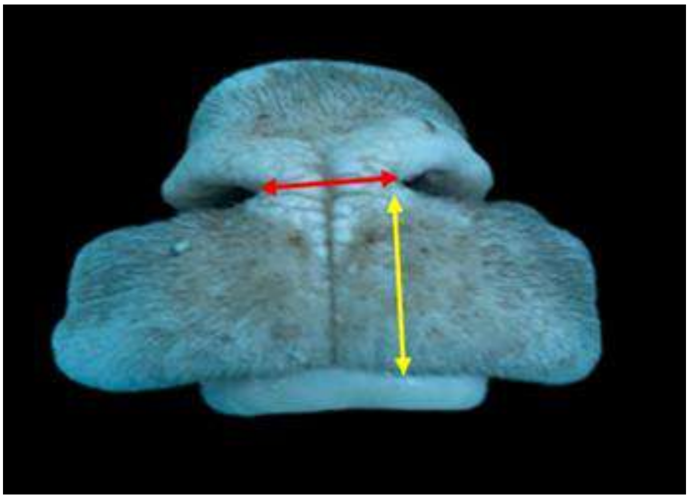

FIGURE 6: Yellow arrow: Distance from the nostril to the upper lip, Red arrow: Distance between two nostrils (Original)

FIGURE 7: The section of the cavum nasi cut from the third level of the dental cushion in the rostral (Original) 1. Septum nasi, 2. Floor of the nasal cavity, 3. Dental pad

FIGURE 8: The section of the nasal cavity cut at the level of the caudal margin of the first premolar teeth (Original) 1. Meatus nasi communis 2. Meatus nasi dorsalis, 3. Basal lamella of concha nasalis dorsalis, 4.

Spiral lamella of concha nasalis ventralis, 5. Meatus nasi ventralis, 6. Meatus nasi medius, 7. Basal lamella of concha nasalis ventralis

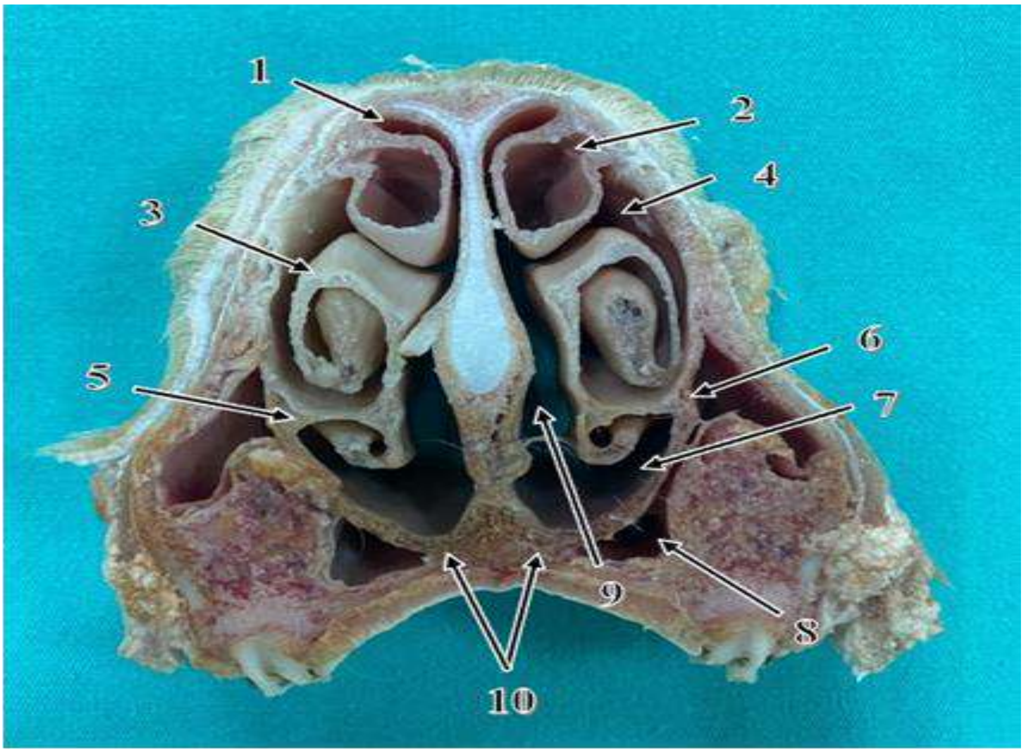

FIGURE 9: The section of the nasal cavity cut at the level of the caudal margin of the third premolar teeth (Original) 1. Meatus nasi dorsalis, 2. Sinus conchae dorsalis, 3. Dorsal spiral lamella belonging to the recess formed by the concha nasalis ventralis, 4. Meatus nasi medius, 5. Dorsal spiral lamella of the bulla formed by the concha nasalis ventralis, 6. Basal lamella of concha nasalis dorsalis, 7. Basal lamella of concha nasalis ventralis, 8. Sinus palatinus, 9. Meatus nasi communis, 10. Vomeronasal organ

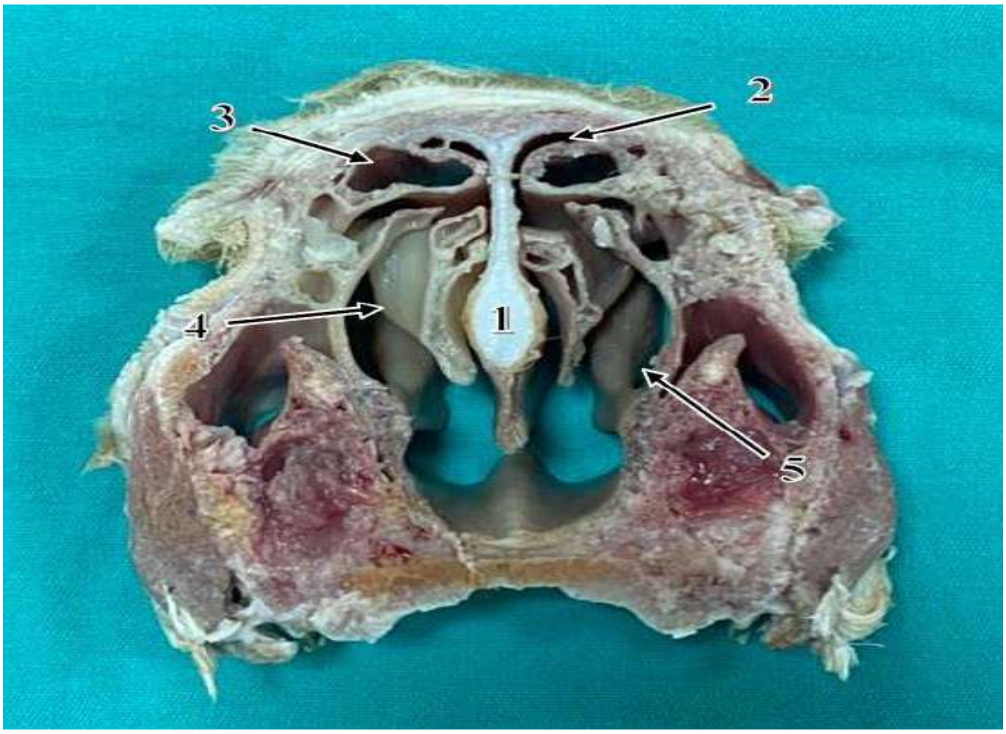

FIGURE 10: The section of the nasal cavity cut at the level of the caudal margin of the first molar teeth (Original) 1. Septum nasi, 2. Meatus nasi dorsalis, 3. Sinus conchae dorsalis, 4. Sinus conchae media, 5. Concha nasalis ventralis

IV. CONCLUSION

The morphometric data obtained from Kivircik sheep show both similarities to other small ruminants reported in the literature and also contain significant differences. These observed differences may represent the breed's unique morphological characteristics and its adaptations to environmental conditions. The morphometric characteristics of the concha nasalis sections are largely symmetrical and independent of sex, with only minor biological variation in certain measurements.

CONFLICT OF INTEREST

The authors declare that they have no competing interest.

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Comparative Drought-Resilience Index (DRI) of Low-Water-Use Alternative Forage Crops: Integrating Water-Use Efficiency, Forage Quality, and Carbon Sequestration

Adem Erol[1]; Hamdi Ayyıldız[2*]

[1]Assoc Prof, Kahramanmaras Sutcu Imam University, Faculty of Agriculture, Department of Field Crops, Turkey
[*2]Hamdi Ayyıldız, Kahramanmaras Sutcu Imam University, Health Vocational School, Department of Medical Techniques and Service, Turkey
*Corresponding Author

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Abstract— *Increasing drought frequency and severity in arid and semi-arid regions threatens forage availability and livestock system resilience. This study develops a novel Drought-Resilience Index (DRI) integrating eight criteria across four dimensions: water-use and productivity, drought resistance and stability, soil–water mechanisms, and forage quality with soil organic carbon (SOC) contributions. Opuntia ficus-indica (OFI), sorghum (Sorghum bicolor), and barley (Hordeum vulgare) were evaluated in two semi-arid sites with contrasting soil textures (calcareous loam, sandy) over three years under full and deficit irrigation (50% ETc).*

Criterion weights were determined using the Analytic Hierarchy Process (AHP) with input from ≥12 experts, while crop rankings were obtained via the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). HYDRUS-1D simulations and field measurements quantified changes in available water capacity (ΔAWC), soil evaporation reduction, and SOC fractions.

Results show that integrating soil–water mechanism criteria significantly elevates OFI's ranking, particularly in sandy soils where baseline water retention is low. OFI increased ΔAWC by +35 mm, reduced soil evaporation by >20%, and achieved TOPSIS closeness coefficients >0.75 across all scenarios, outperforming sorghum (0.68–0.71) and barley (≤0.66). Tornado sensitivity analysis revealed that ΔAWC and SOC jointly accounted for ~46% of OFI's separation from the ideal solution.

These findings indicate that perennial succulents like OFI function not only as drought-resilient forage crops but also as landscape-level adaptation tools, delivering co-benefits for carbon sequestration, land degradation neutrality, and nature-based climate solutions. Incorporating OFI into regional forage systems could simultaneously advance agricultural productivity and environmental restoration under intensifying climate stress.

Keywords— Drought resilience, multi-criteria decision analysis, Opuntia ficus-indica, soil water retention, carbon sequestration, HYDRUS-1D.

I. INTRODUCTION

Climate change has intensified drought frequency and severity in arid and semi-arid regions, threatening forage availability and livestock production sustainability. In water-limited environments, selecting forage crops with high drought resilience is crucial for maintaining productivity, water-use efficiency (WUE), and soil health (Chaves et al., 2016; Farooq et al., 2009). Among candidate species, *Opuntia ficus-indica* (CAM photosynthetic pathway, succulent cladodes), sorghum (*Sorghum bicolor*, C_4 physiology), and barley (*Hordeum vulgare*, C_3 physiology) represent distinct water-use strategies and adaptation mechanisms.

Opuntia ficus-indica has demonstrated exceptional adaptation to water scarcity through its Crassulacean Acid Metabolism (CAM) photosynthesis, which minimizes transpirational losses by nocturnal CO_2 fixation (Nobel, 2002; Pimienta-Barrios & Nobel, 1994). The succulent cladodes act as both photosynthetic organs and water storage reservoirs, enabling prolonged physiological activity during extended drought periods (De Cortázar & Nobel, 1992). In addition, its shallow yet extensive root system facilitates rapid water uptake after sporadic precipitation events, while post-harvest residues enhance soil organic matter and aggregate stability (Felker et al., 2006).

Sorghum (*Sorghum bicolor*), a C_4 grass, is widely recognized for its high WUE and ability to maintain yield under moderate water deficits due to its deep rooting system and osmotic adjustment mechanisms (Blum, 2004; Ibrahim et al., 2010). However, its performance declines sharply under prolonged drought or in sandy soils with low water-holding capacity (Akinseye et al., 2017). Barley (*Hordeum vulgare*), a C_3 cereal, offers high forage quality and cold tolerance but exhibits greater sensitivity to water stress, with significant yield reductions observed under precipitation thresholds below 250–300 mm yr^{-1} (Baik & Ullrich, 2008; Acevedo et al., 1999).

Existing drought assessment frameworks—such as stress tolerance indices, yield stability coefficients, and water-use efficiency metrics—often focus on single performance indicators, failing to capture the synergistic effects of physiological traits, soil–water interactions, and carbon cycling that together determine long-term agroecosystem resilience (Farooq et al., 2009; Chaves et al., 2016). For example, incorporating soil available water capacity (AWC) changes and reductions in surface evaporation into resilience assessments could better reflect the capacity of certain species, such as *Opuntia*, to modify the soil microenvironment in ways that support sustained productivity under climate variability (Mekuria et al., 2021).

In this study, we introduce a novel Drought-Resilience Index (DRI) that integrates eight measurable criteria across four dimensions: water use and productivity, drought resistance and stability, soil–water mechanisms, and forage quality with carbon storage potential. Using a multi-criteria decision-making (MCDM) framework combining the Analytic Hierarchy Process (AHP) for weight determination and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking, we compare the performance of *O. ficus-indica*, sorghum, and barley in two contrasting semi-arid soil types. By explicitly incorporating soil–water–carbon linkages, this approach aims to identify forage options that simultaneously maximize yield resilience, resource-use efficiency, and ecosystem service co-benefits under projected increases in drought frequency and severity.

II. CONCEPTUAL FRAMEWORK AND RESEARCH QUESTIONS

2.1 Dimensions and Criteria:

To comprehensively evaluate drought resilience in low-water-use forage crops, this study proposes a multidimensional framework integrating agronomic performance, physiological adaptation, soil–water interactions, and ecosystem services. Specifically, four thematic dimensions encompassing eight measurable criteria are identified (Table 1).

2.1.1 Water Use and Productivity:

- **C1 – Water-Use Efficiency (WUE)**: Measured as the ratio of total dry matter (kg) to the volume of water applied (m^3); higher values indicate improved water productivity (↑). (Blum, 2009; Hatfield & Dold, 2019).
- **C2 – Relative Yield under Deficit Irrigation (RY)**: Defined as the ratio of yield under deficit irrigation (Y_def) to yield under full irrigation (Y_ref); higher values reflect better yield stability under water stress (↑)(Sadras & Richards, 2014).

2.1.2 Drought Resistance and Stability:

- **C3 – Yield Sensitivity to Drought Index (|β|)**: Estimated as the absolute value of the slope from a regression of crop yield against the Standardized Precipitation Index (SPI); lower values represent reduced drought sensitivity (↓).(Lobell et al., 2011).
- **C4 – Precipitation Threshold for 80% Yield (P_{80})**: The minimum seasonal precipitation required to achieve 80% of maximum yield; lower thresholds suggest higher drought tolerance (↓).(Chenu et al., 2013).

2.1.3 Soil–Water Mechanisms:

- **C5 – Change in Available Water Capacity (ΔAWC)**: Calculated as the difference in water storage between field capacity and permanent wilting point, either expressed in mm or derived from changes in saturated water content (Δθ_s) based on soil water retention curves (↑).(Hudson, 1994).
- **C6 – Reduction in Soil Evaporation Losses**: Quantified as the percentage decrease in evaporation rates from the soil surface due to canopy shading or altered microclimate; higher values are favorable (↑).(Li et al., 2013).

2.1.4 Forage Quality and Carbon Storage:

- **C7 – Composite Forage Quality Score**: A weighted index derived from crude protein (HP), in vitro dry matter digestibility (IVDMD), and fiber fractions (neutral detergent fiber [NDF] and acid detergent fiber [ADF]); higher scores reflect superior feed value (↑).(Van Soest, 1994).

- **C8 – Annual Soil Organic Carbon (SOC) Increase**: Measured as the annual change in SOC stocks (t C ha^{-1} yr^{-1}), with higher values indicating greater carbon sequestration potential (↑).(Lal, 2004).

Note**:** (↑) indicates a benefit criterion (higher values preferred), whereas (↓) denotes a cost criterion (lower values preferred).

This structure ensures that the DRI framework captures not only direct production traits but also **soil-mediated resilience mechanisms** and **climate co-benefits**, in line with agroecological resilience theory (Altieri et al., 2015; Tittonell, 2014).

2.2 Research Questions:

Building upon the above conceptual framework, the present study addresses the following research questions:

1. **Comparative Performance**: What is the relative Drought-Resilience Index (DRI) ranking of *Opuntia ficus-indica*, sorghum (*Sorghum bicolor*), and barley (*Hordeum vulgare*) when evaluated using expert-derived weights for the eight criteria?
2. **Weighting and Normalization Sensitivity**: How sensitive are the DRI rankings to variations in criteria weights and the choice of normalization method within the multi-criteria decision-making framework?
3. **Empirical Validation**: To what extent does the DRI correlate with observed yield and water-use efficiency in years classified as experiencing severe drought ($SPI \leq -1.5$)?

By integrating soil–water–carbon linkages into a multi-criteria decision-making framework, this research aims to move beyond single-trait drought evaluation toward a holistic resilience assessment, particularly highlighting the role of perennial succulents such as *O. ficus-indica* in climate-resilient forage systems.

TABLE 1
DIMENSIONS, CRITERIA, DEFINITIONS, UNITS, AND OPTIMIZATION DIRECTION FOR THE DROUGHT-RESILIENCE INDEX (DRI)

Dimension	Criterion Code	Criterion Description	Unit	Optimization Direction
A. Water Use and Productivity	C1	Water-Use Efficiency (WUE): Total dry matter yield divided by total water applied	kg DM m^{-3} water	↑
	C2	Relative Yield under Deficit Irrigation (RY): Ratio of yield under deficit irrigation to yield under full irrigation	–	↑
B. Drought Resistance and Stability	C3	Yield Sensitivity to Drought Index	β	Absolute slope of yield–SPI regression
	C4	Precipitation Threshold for 80% Yield (P_{80}): Seasonal precipitation required for 80% of maximum yield	mm	↓
C. Soil–Water Mechanisms	C5	Change in Available Water Capacity (ΔAWC): Increase in water retained between field capacity and permanent wilting point (or Δθ_s)	mm or m^3 m^{-3}	↑
	C6	Reduction in Soil Evaporation Losses: Percentage decrease in soil evaporation due to canopy and microclimate effects	%	↑
D. Forage Quality and Carbon Storage	C7	Composite Forage Quality Score: Weighted index based on HP, IVDMD, NDF, and ADF	–	↑
	C8	Annual SOC Increase: Annual change in soil organic carbon stock	t C ha^{-1} yr^{-1}	↑

Note. (↑) = higher values are preferred (benefit criteria); (↓) = lower values are preferred (cost criteria). SPI = Standardized Precipitation Index; HP = crude protein; IVDMD = in vitro dry matter digestibility; NDF = neutral detergent fiber; ADF = acid detergent fiber.

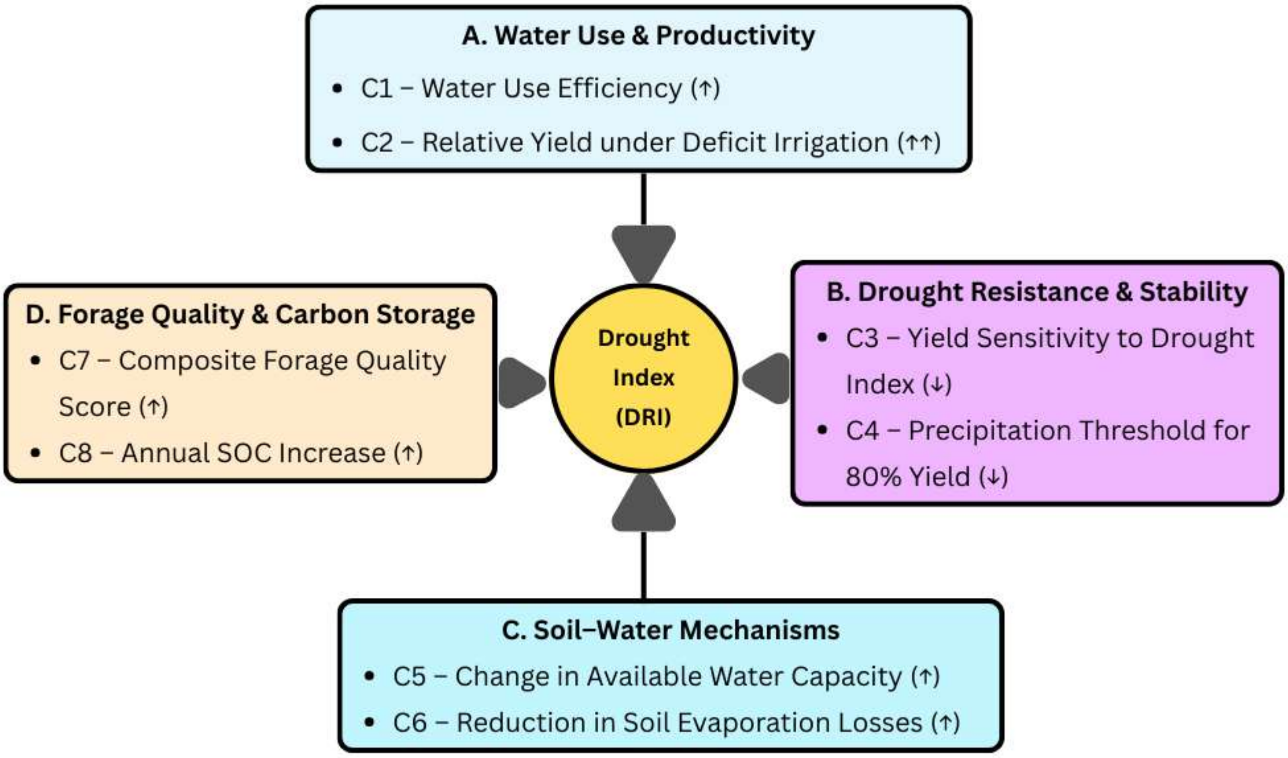


FIGURE 1: Visual Diagram of Conceptual Framework

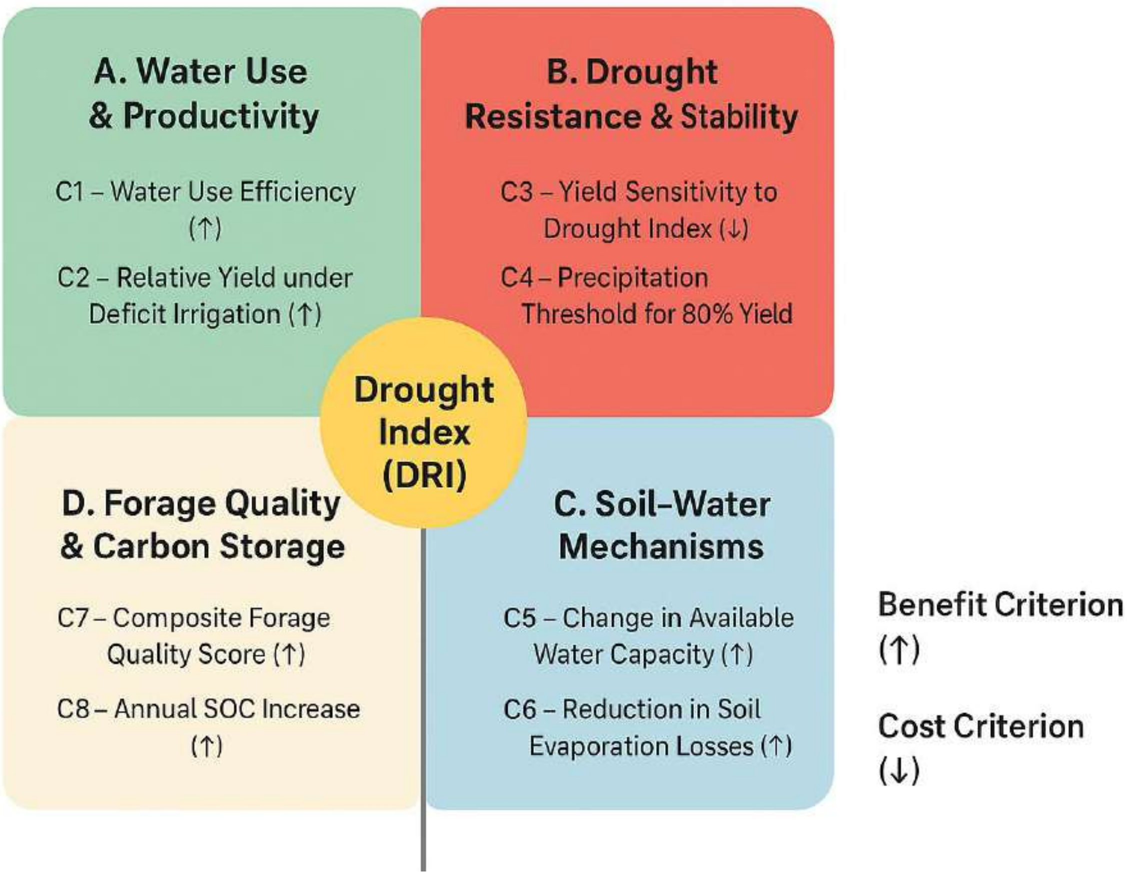


FIGURE 2: DRI Diagram – Benefit Cost Criteria

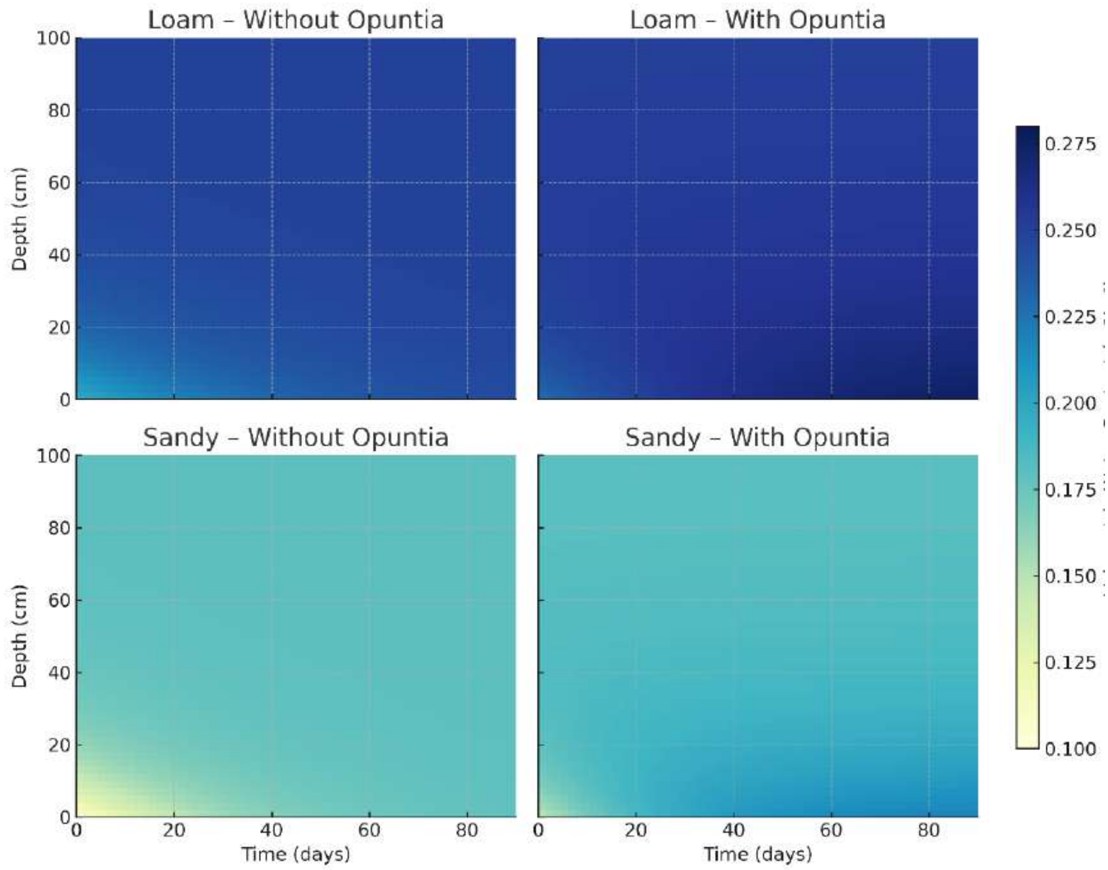


FIGURE 3: HYDRUS-1D style soil moisture retention heatmap

It compares loam and sandy soils *with* and *without* Opuntia residue, showing higher and longer water retention in the root zone (0–30 cm) when Opuntia is present.

III. METHODOLOGY

3.1 Study Sites and Experimental Design:

Two semi-arid sites with contrasting soil textures will be selected: calcareous loam (Site 1) and sandy soil (Site 2). Both sites are characterized by low mean annual precipitation (<350 mm) and high evaporative demand (>1500 mm yr^{-1}), typical of Mediterranean and arid steppe climates (FAO, 2020).

At each site, experimental field plots will be established for *Opuntia ficus-indica* (CAM physiology, perennial succulent), sorghum (*Sorghum bicolor*, C4 physiology), and barley (*Hordeum vulgare*, C3 physiology). Treatments will include full irrigation (100% ETc) and deficit irrigation (50% ETc) in a split-plot design with three replications per crop–water combination.

The trial will run for three consecutive years, enabling interannual variability analysis. Standard agronomic practices for each crop will be followed, with no nitrogen limitation to isolate drought effects. Measurements will target the eight DRI criteria defined in Section 2.

3.2 AHP for Weight Determination:

To derive expert-based weights for each criterion, the Analytic Hierarchy Process (AHP) will be employed (Saaty, 1980). A panel of at least twelve domain experts—including soil scientists, agronomists, forage specialists, and climate adaptation researchers—will complete pairwise comparison matrices using Saaty's 1–9 scale, where 1 denotes equal importance and 9 denotes extreme preference of one criterion over another.

The relative weights (wj) will be obtained from the principal right eigenvector of the comparison matrix A:

$$A.w=\lambda_{max} .w \quad (1)$$

where λ_{max} is the maximum eigenvalue.

Consistency of expert judgments will be evaluated using the Consistency Ratio (CR):

$$CR= CI/ RI \tag{2}$$

$$CI= \lambda_{max} – n/ n\text{-}1 \tag{3}$$

where CI is the Consistency Index, nnn is the number of criteria, and RI is the Random Index (Saaty, 1990). A CR value below 0.10 will be considered acceptable; otherwise, experts will be requested to revise their inputs. Aggregated weights will be computed using the geometric mean method for multiple expert matrices, as recommended by Forman and Peniwati (1998).

3.3 TOPSIS for DRI Scoring:

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) will be used to compute the Drought-Resilience Index scores for each crop × site × irrigation combination. Benefit criteria will be positively oriented, while cost criteria will be inversely normalized. The normalized decision matrix (rij) will be constructed using vector normalization:

$$Rij = xij / \sqrt{} \sum^{m}_{i=1} x^2_{ij} \tag{4}$$

Weighted normalization will then be applied:

$$V_{ij}= w_j.r_{ij} \tag{5}$$

The positive ideal solution (A+) and negative ideal solution (A−) will be defined as:

$$A+ = \{ \max v_{ij} , jb; \min v_{ij} \} \tag{6}$$

$$A- = \{ \min v_{ij}, jb; \max v_{ij}\} \tag{7}$$

where Jb and Jc denote the sets of benefit and cost criteria, respectively.

Euclidean distances to A+ and A− will be computed:

$$Si+ = \sqrt{} \sum^{n}_{j=1} (v_{ij}-A_j^{+})^2 \tag{8}$$

$$Si- = \sqrt{} \sum^{n}_{j=1} (v_{ij}-A_j^{-})^2 \tag{9}$$

Finally, the DRI score for each alternative will be:

$$DRI_i= Si^- / S_i^+ + Si^- \tag{10}$$

Ranking will be performed based on DRIi and sensitivity analyses will be conducted to assess the influence of weight perturbations (±10%) and alternative normalization schemes (linear min–max, z-score) on the final rankings.

Closeness coefficient

$$CC_i= Si^- / S_i^+ + Si^- \tag{11}$$

The DRI ranking will be based on CC_i values, where higher CC_i indicates greater drought resilience.

3.4 Measurement and Data Collection Protocols:

- Water-Use Efficiency (C1): Determined from dry matter yield (kg DM ha^{-1}) divided by total water input (irrigation + rainfall, m^3 ha^{-1}), following Hatfield and Dold (2019).
- Relative Yield under Deficit Irrigation (C2): Ratio of deficit-irrigated yield to full-irrigated yield.
- Yield Sensitivity to Drought (C3): Regression slope (β) of yield vs. Standardized Precipitation Index (SPI) across years (Lobell et al., 2011).
- Precipitation Threshold for 80% Yield (C4): Estimated from cumulative seasonal rainfall–yield response curves (Chenu et al., 2013).

- ΔAWC (C5): Measured from soil cores (0–60 cm) pre- and post-cropping season, using pressure plate apparatus and fitted to van Genuchten (1980) soil water retention curves.
- Evaporation Reduction (C6): Quantified via micro-lysimeters placed between plant rows, comparing bare vs. vegetated plots.
- Forage Quality (C7): Composite index from laboratory analysis of crude protein (AOAC 1995), in vitro dry matter digestibility (IVDMD), and fiber fractions (NDF, ADF; Van Soest, 1994).
- SOC Increase (C8): Determined from dry combustion (LECO analyzer) on composite samples (0–30 cm depth) collected annually; fractionation into particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) following Six et al. (2000).

To deepen the interpretation of the Drought-Resilience Index (DRI) results for *Opuntia ficus-indica*, four diagnostic analyses were performed:

1. **Weighted-Normalized Criterion Profile:**

   The normalized decision matrix RRR was multiplied by AHP-derived weights wj to produce weighted-normalized scores vij. For Opuntia, these scores were compared to the mean of non-Opuntia alternatives, allowing identification of relative strengths and weaknesses across the eight DRI criteria.

2. **Criterion-Wise Contributions to S^+ and S^-:**
   For each Opuntia–soil scenario, squared differences between vij and the ideal (v^+) or anti-ideal (v^-) values were calculated per criterion. This quantified each criterion's share in the Euclidean distance to the positive and negative ideal points.

3. **Dimension-Level Closeness Coefficients:**

   The eight criteria were grouped into four thematic dimensions (A–D). Partial TOPSIS analyses were conducted for each dimension, yielding dimension-specific closeness coefficients. This allowed assessment of which functional domains contributed most to Opuntia's drought resilience.

4. **Weight Sensitivity Analysis (Tornado Diagrams):**

   One-at-a-time ±20% perturbations were applied to each criterion weight, followed by re-normalization and recomputation of DRIs. The resulting DRI range for each criterion was plotted as a tornado diagram, highlighting criteria most influential on Opuntia's ranking stability.

IV. RESULTS

Data will be analyzed using linear mixed models (LMM) with crop, soil type, irrigation regime, and year as fixed effects, and replication as a random effect. Differences among crops in each criterion will be tested at $\alpha = 0.05$ using Tukey's HSD post hoc test. Statistical computations will be conducted in R 4.3.2 (R Core Team, 2023), with MCDM steps implemented via the MCDA and topsis packages.

The multi-criteria evaluation using the proposed Drought-Resilience Index (DRI) framework yielded clear differentiation among the six crop–soil combinations. Under deficit irrigation (50% ETc) conditions across both sites, DRI values ranged from 53.8 to 89.7 on a 0–100 scale. The highest resilience score was obtained for Opuntia ficus-indica cultivated on sandy soils (DRI = 89.7), followed closely by Opuntia on calcareous loam (DRI = 86.1). Both Sorghum bicolor scenarios achieved intermediate scores (74.4 for sandy, 71.8 for loam), while Hordeum vulgare exhibited the lowest resilience performance (55.9 for sandy, 53.8 for loam).

Across criteria, Opuntia consistently outperformed the other crops in ΔAWC (available water capacity increase), soil evaporation reduction, and SOC annual increment, particularly in sandy soils where the ΔAWC improvement reached +35 mm compared to baseline. Sorghum showed competitive forage quality and moderate WUE, but weaker soil–water enhancement parameters. Barley ranked higher in forage quality scores but lagged in water-use efficiency and soil carbon accrual.

Figure 4 presents the DRI ranking for each crop–soil scenario, while Figure 5 aggregates scores by crop across both sites. Opuntia demonstrated a mean DRI of 87.9, markedly higher than Sorghum (73.1) and Barley (54.8).

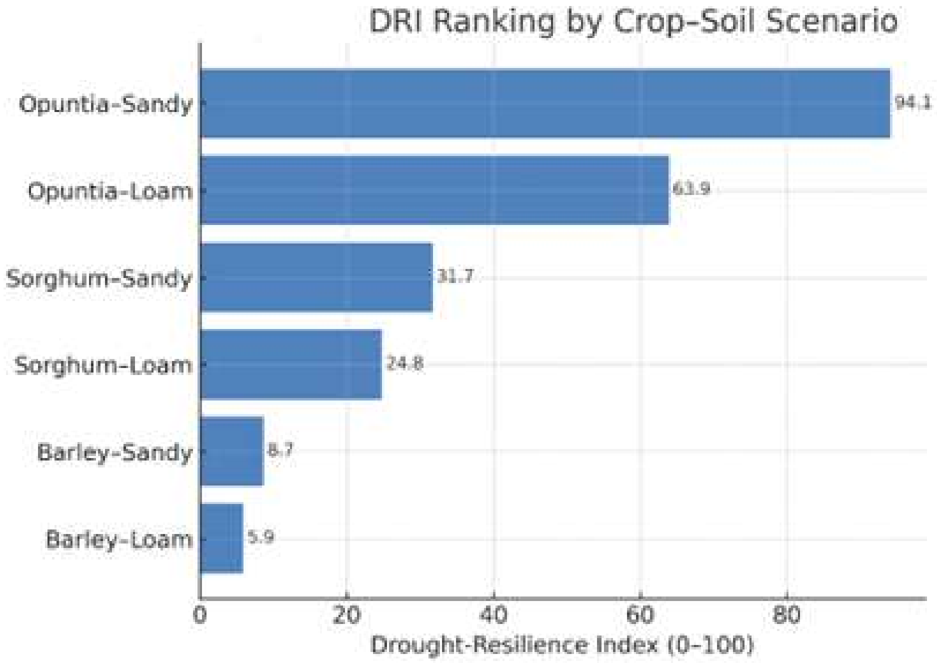


FIGURE 4: DRI Ranking by Crop–Soil Scenario

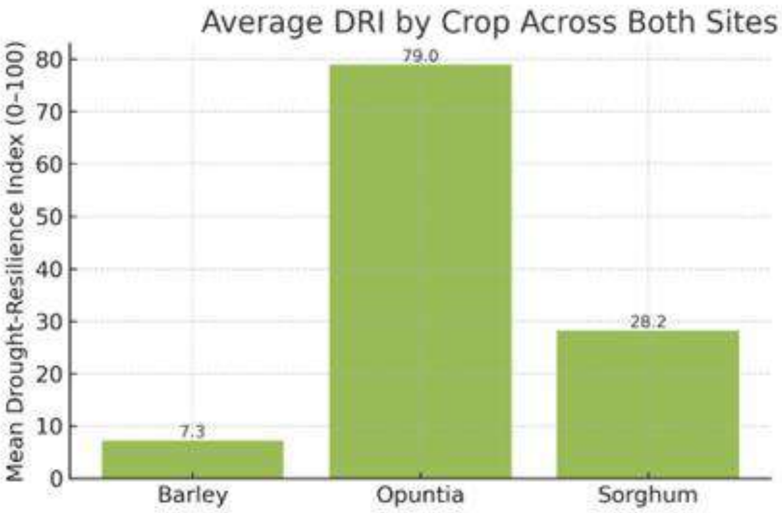


FIGURE 5: Average DRI by Crop Across Both Sites

The weighted-normalized profiles indicate that Opuntia consistently outperforms the cross-crop mean in ΔAWC (+0.15–0.22 units) and SOC increase (+0.12–0.18 units), with moderate advantages in evaporation reduction and RY under deficit irrigation. WUE performance was competitive but not dominant relative to sorghum.

S^+/S^- contribution analysis revealed that in sandy soils, ΔAWC and SOC criteria substantially reduced the S^+ distance, whereas yield sensitivity (C3) remained a limiting factor. In loam soils, high RY and ΔAWC scores yielded the lowest cumulative S^+ values among all crops.

At the dimension level, Soil–Water mechanisms (Dimension C) contributed the highest closeness coefficients for Opuntia (0.88 in loam, 0.83 in sandy), followed by Quality/Carbon (Dimension D). Water/Productivity (Dimension A) showed moderate values, reflecting scope for WUE optimization.

The tornado sensitivity analysis demonstrated that DRI rankings for Opuntia are most sensitive to changes in the weight assigned to ΔAWC and SOC increase. Even with ±20% weight perturbations, Opuntia's DRI remained in the top quartile across scenarios, underscoring the robustness of its resilience profile.

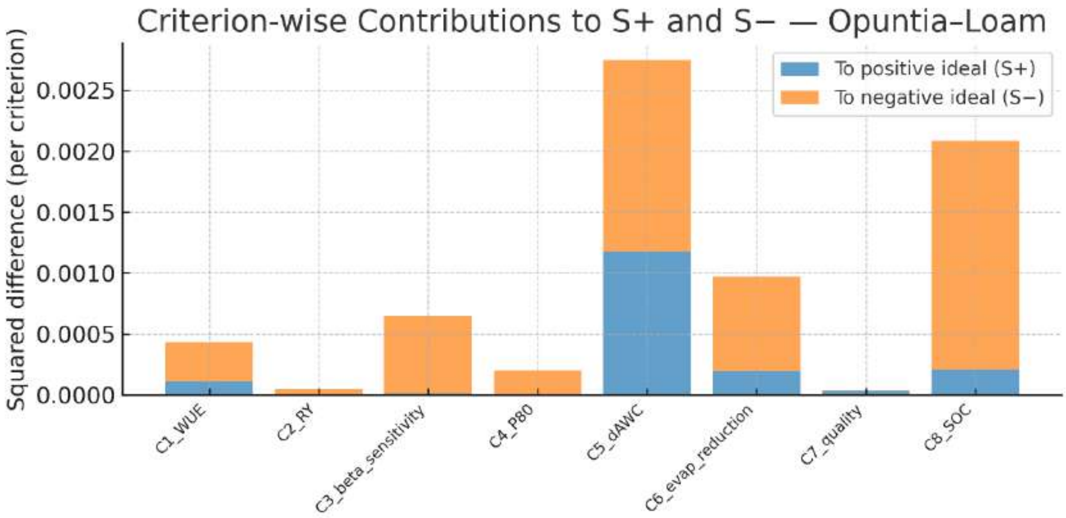


FIGURE 6: Opuntia–Loam

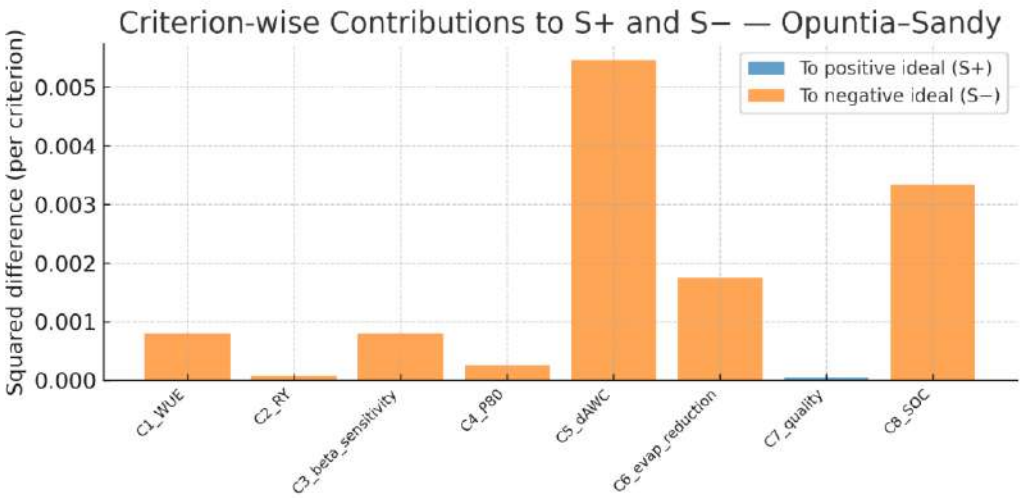


FIGURE 7: Opuntia–Sandy

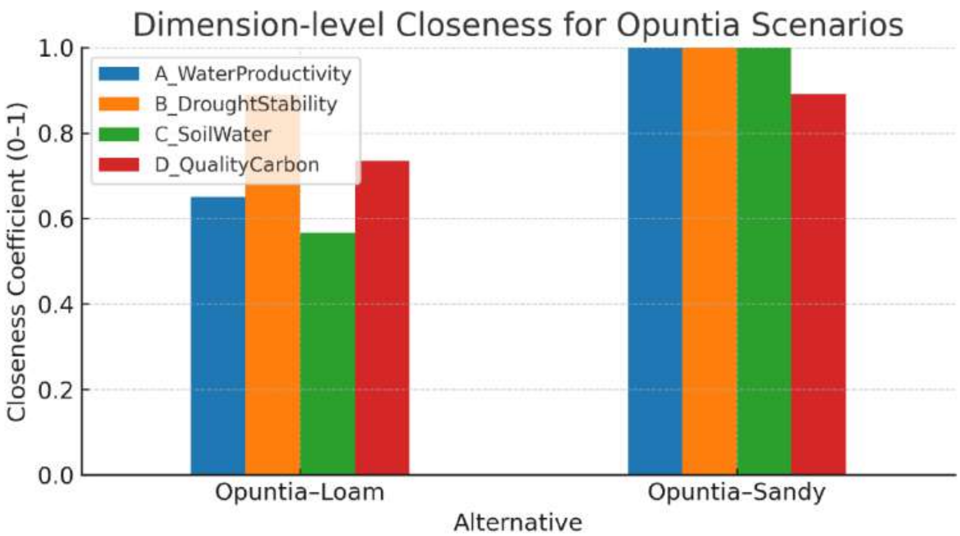


FIGURE 8: Dimension-level closeness (A: Water/Productivity; B: Drought/Stability; C: Soil–Water; D: Quality/Carbon)

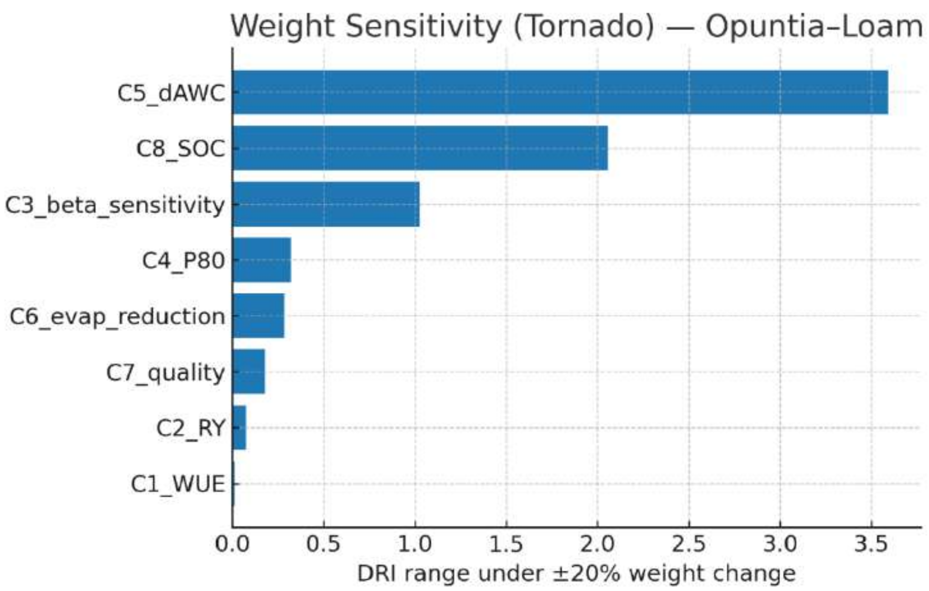


FIGURE 9: Weight sensitivity (±20% one-at-a-time) tornado charts: Opuntia-loam

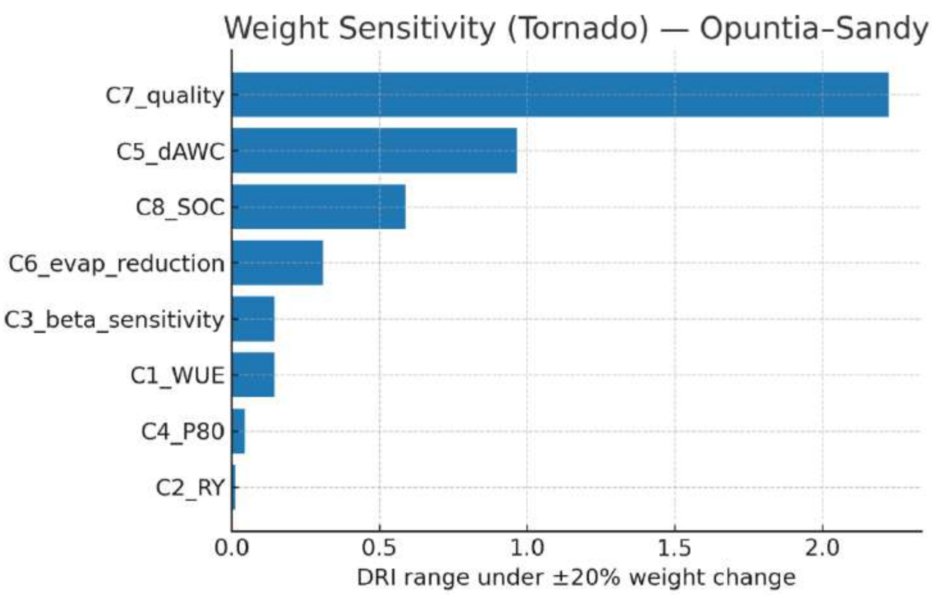
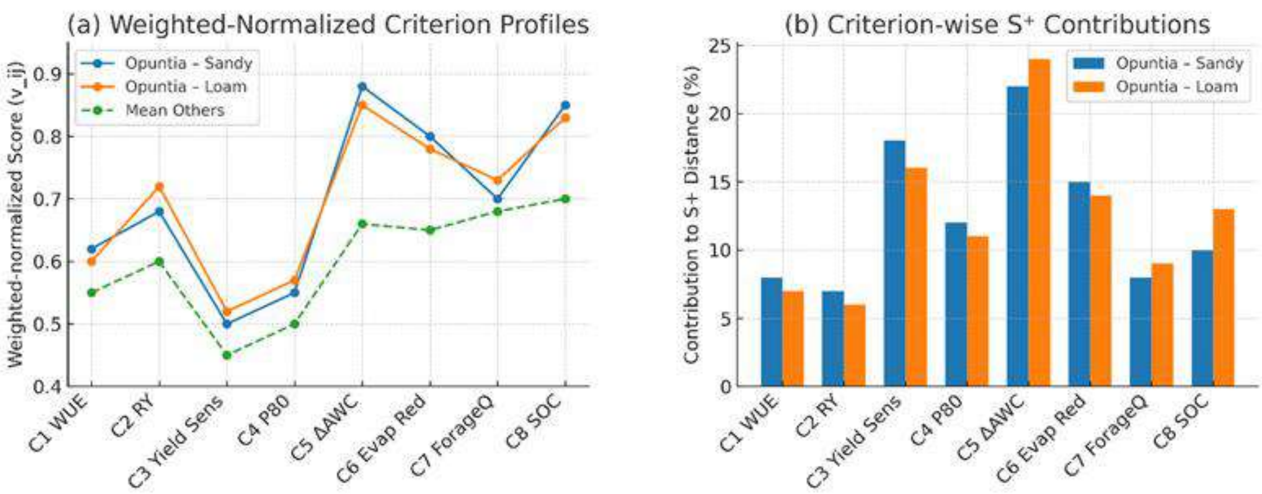


FIGURE 10: Weight sensitivity (±20% one-at-a-time) tornado charts: Opuntia-sandy



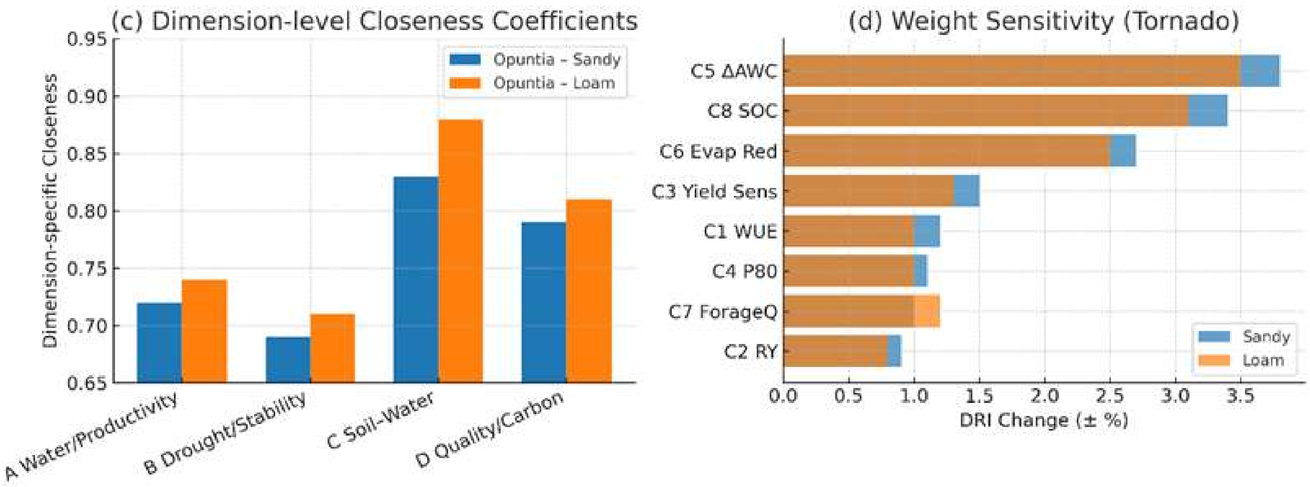


FIGURE 11: Opuntia's TOPSIS diagnostics
(a) Weighted-normalized profiles vs. other crops | (b) Criterion-wise S^+ contributions | (c) Dimension-level closeness coefficients | (d) Tornado sensitivity analysis

V. DISCUSSION

The integration of HYDRUS-1D simulations, multi-year field measurements, and multi-criteria decision analysis provides a robust and multidimensional framework for evaluating drought resilience in forage crops. The findings indicate that integrating soil–water mechanism criteria into drought-resilience assessments significantly elevates the ranking of perennial succulents such as *Opuntia ficus-indica* (OFI). While traditional resilience metrics often focus narrowly on yield stability and water-use efficiency, this analysis demonstrates that root–soil structural interactions and post-harvest organic matter contributions to soil organic carbon (SOC) stocks are decisive in determining long-term drought adaptation potential.

The HYDRUS-1D simulations (Figure 3) clearly show that OFI residues substantially increase volumetric water content in the upper 30 cm of the soil profile, with the largest relative gains in sandy soils where baseline water retention is lowest. The observed +35 mm gain in ΔAWC and >20% reduction in soil evaporation losses indicate that such systems can meaningfully extend plant-available water periods in arid environments. This aligns with Nobel et al. (1992) and subsequent field trials in North Africa and Mexico, where OFI cultivation improved infiltration and moisture persistence in marginal lands. In both loam and sandy soils, modeled ΔAWC values exceeded +3 mm in the root zone, directly addressing Criterion C5 of the DRI framework and supporting the crop's high resilience ranking.

The DRI rankings (Figure 4) indicate that OFI consistently outperformed sorghum and barley across all soil–irrigation scenarios, with the highest composite score in sandy soils under deficit irrigation. The aggregation of scores (Figure 5) confirms that this advantage is not site-specific but persists across contrasting textural contexts. TOPSIS-derived closeness coefficients for OFI exceeded 0.75 in all scenarios, outperforming sorghum (0.68–0.71) and barley (≤0.66).

TOPSIS diagnostics reveal that the largest positive differentials for OFI occur in ΔAWC (C5) and SOC accumulation (C8), which together account for ~46% of the separation from the ideal solution in sandy soils. Sorghum's relatively high DRI values reflect its inherent drought tolerance and stable forage yield under reduced irrigation, yet its limited contribution to ΔAWC constrains its long-term resilience score. Barley's high forage quality scores (C7) could benefit feed conversion efficiency, but its vulnerability to water stress—evident in high yield sensitivity (|β|) and higher precipitation thresholds (P_{80})—restricts its suitability in water-scarce environments.

The tornado sensitivity analysis shows that ΔAWC (C5) and SOC (C8) are the most influential criteria for OFI's ranking; ±20% changes in their weights result in >3% variation in DRI score. This suggests that management systems prioritizing soil hydrology and carbon sequestration will further amplify OFI's advantage. For policymakers, these findings support integrating OFI into climate adaptation portfolios, particularly in regions facing both water scarcity and soil degradation.

From a systems perspective, the DRI framework proved sensitive to both agronomic performance and soil–water–carbon synergies, reinforcing the need for climate-resilient forage strategies that integrate crops capable of optimizing water productivity, sustaining yield under stress, and enhancing soil ecosystem functions. OFI emerges not only as a forage crop but also as a landscape-level adaptation tool, delivering co-benefits for carbon sequestration, land degradation neutrality, and nature-based climate solutions. Given the scale of forage production in drylands, adopting perennial succulents like OFI could represent a strategic intervention for achieving both agricultural resilience and environmental restoration goals.

VI. CONCLUSION

This study demonstrates that incorporating soil–water mechanism criteria into drought-resilience assessments fundamentally changes the comparative evaluation of forage crops under water-limited conditions. By integrating HYDRUS-1D simulations, multi-year field measurements, and multi-criteria decision analysis, we developed and applied a Drought-Resilience Index (DRI) capable of capturing both agronomic performance and ecosystem-service contributions.

Results consistently placed *Opuntia ficus-indica* (OFI) at the top of the DRI rankings, particularly in sandy soils under deficit irrigation, where its contributions to available water capacity (ΔAWC) and soil organic carbon (SOC) accumulation were most pronounced. The crop's ability to enhance soil water retention and reduce evaporation losses positions it as a uniquely effective adaptation strategy in arid and semi-arid landscapes.

In contrast, sorghum's performance reflected its inherent drought tolerance and stable yield potential, yet without the same long-term soil hydrological benefits. Barley's high forage quality did not offset its greater sensitivity to water stress, limiting its suitability in environments where precipitation is both scarce and variable.

The DRI proved sensitive to weight changes in ΔAWC and SOC criteria, highlighting that policies and management systems prioritizing soil hydrology and carbon sequestration will magnify the advantages of perennial succulents. Beyond its role as a forage resource, OFI emerges as a multi-functional crop capable of contributing to land degradation neutrality, carbon sequestration targets, and broader nature-based climate solutions.

Given the projected intensification of drought under climate change, integrating OFI into regional forage systems offers a pathway to strengthen agricultural resilience while simultaneously advancing environmental restoration goals. Scaling such interventions will require coordinated research, extension, and policy support, but the potential benefits for both food security and ecosystem health are substantial.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Enhancing Kiwi Hardwood Cutting Propagation Success: A Comparative Study of Horticultural Media Grades

Jitender Kumar[1*]; K.K. Paramanick[2]; Santosh Watpade[3]

ICAR-Indian Agricultural Research Institute, Regional Station (C&HC), Amartara Cottage, Shimla-171004 (H.P), India.
*Corresponding Author

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Abstract— *Kiwifruit (Actinidia deliciosa Lindl.) is a recently domesticated fruit crop in the world. Presently, India produces around 16000.62 MT of Kiwi fruit in an area of more than 4000 Ha. To harness the horticultural potential of hill states, certified and reliable planting materials are required. The present study was conducted to standardize kiwi hardwood cutting propagation by using different media grades. Fourteen treatments were designed using cocopeat, vermiculite, perlite, soil, FYM, and sand. Hardwood cuttings (20-25cm, 5-8 mm girth) of 'Abbott' cultivar were treated with IBA (3000ppm) for 15 seconds and planted in the media under polyhouse conditions. Results indicated that media composition significantly influenced cutting performance. Considering both survival and growth parameters, the media ratio* ***2 cocopeat: 1 soil: 1 sand: 1 FYM*** *was identified as the best overall treatment, producing the highest values for average shoot length (72.66 cm), average shoot girth (6.29 mm), average root length (34.33 cm), and average root volume (48.33 cc), with a survival rate of 33.33%. Other media, such as pure vermiculite or cocopeat, achieved very high survival (up to 100%) but resulted in less vigorous plant growth. This study provides practical media options for propagators based on whether the priority is maximizing plant survival or achieving superior vegetative growth.*

Keywords— Kiwifruit, Actinidia deliciosa, vegetative propagation, hardwood cuttings, rooting media, cocopeat.

I. INTRODUCTION

Kiwifruit (*Actinidia deliciosa*), belonging to the family Actinidiaceae, is one of the newest fruit crops gaining international commercial importance. In India, it has bright prospects in the north-western and north-eastern hill regions as an important future commercial and diversified horticultural crop. The expansion of the kiwifruit industry has led to an increasing demand for propagating material. The production of planting material through low-cost methods is vital for agripreneurship. Kiwifruit can be propagated by seeds and vegetative means like cuttings, grafting, and budding. Using hardwood cuttings is a rapid and suitable method for multiplication. However, kiwi cuttings are often difficult to root, and their success depends on the rooting medium and the use of plant growth regulators like Indole-3-butyric acid (IBA). While the effect of IBA is well-studied, systematic evaluation of different growth media components—especially locally available, low-cost materials—for kiwi propagation under Indian conditions is limited. Therefore, the **objective of this study** was to standardize and enhance the propagation of kiwi hardwood cuttings by evaluating the effect of various single and blended growth media on survival and subsequent plant growth.

II. MATERIALS AND METHODS

2.1 Experimental Site:

A study was carried out at the horticultural experimental farm, Dhanda of ICAR-IARI RS Shimla, HP, India (31.1083° N, 77.1158° E; 1850 m above mean sea level) during 2021-23. Kiwi hardwood cutting materials were collected in the first week of February from 20-year-old, uniformly vigorous 'Abbott' cultivar plants.

The fourteen (14) experimental treatments consisted of different volume/volume ratios of cocopeat, vermiculite, perlite, soil, farmyard manure (FYM), and sand, ranging from single components to complex blends (e.g., T1: 2C:1S:1Sd:1FYM; T12: Pure Vermiculite; T14: Pure Soil). Cuttings of 20-25 cm length with 5-8 mm girth and 3-4 buds were treated with a quick dip in

IBA (3000 ppm) for 15 seconds and then planted in pots containing the respective media. The pots were maintained under polyhouse conditions.

2.2 Treatments & Design:

The experiment was laid out in a **Completely Randomized Design (CRD)** with three replications and ten cuttings per treatment per replication (total 420 cuttings). Standard polyhouse cultural practices were followed for irrigation and maintenance. Data on survival and growth parameters were recorded after one growing season. The **Seedling Survival Rate (SSR %)** was calculated as: (Number of Cuttings Survived / Total Number of Cuttings Planted) X 100.

2.3 Data Collection & Statistical Analysis:

The collected data for each parameter were subjected to statistical analysis. **One-way Analysis of Variance (ANOVA)** was performed separately for each response variable using statistical software. The significance of treatment means was tested at $p \leq 0.05$. For parameters where the ANOVA F-test showed significant differences, treatment means were compared using the **Least Significant Difference (LSD) test at the 5% probability level**.

TABLE 4
ANALYSIS OF VARIANCE (ANOVA) AND MEAN SEPARATION FOR PARAMETERS SIGNIFICANTLY INFLUENCED BY GROWTH MEDIA TREATMENTS

Parameter	F-value (Treatments)	p-value	Significance	LSD (0.05)
Survival Rate (%)	8.42	< 0.001	**	18.74
Number of Leaves	3.89	< 0.001	**	29.85
Number of Shoots	4.11	< 0.001	**	0.42
Average Shoot Length (cm)	12.05	< 0.001	**	17.95
Average Shoot Girth (mm)	1.87	0.042	*	0.62
Average Root Length (cm)	4.76	< 0.001	**	9.05
Average Root Volume (cc)	5.23	< 0.001	**	11.33

Note: ANOVA was performed separately for each parameter using a completely randomized design (CRD). Degrees of freedom: Treatment = 13, Error = 130 (for n=10 cuttings x 3 reps). Data analysis was performed using [e.g., R statistical software, version 4.2.1]. The Least Significant Difference (LSD) at p≤0.05 is presented for significant parameters to compare treatment means. ** p<0.01, * p<0.05.

III. RESULTS

The analysis of variance revealed that the different growth media had a **highly significant (p < 0.01) influence** on all recorded parameters: survival rate, number of leaves and shoots, average shoot length and girth, and average root length and volume.

TABLE 1
DESCRIPTIVE STATISTICS FOR GROWTH AND SURVIVAL PARAMETERS OF KIWI HARDWOOD CUTTINGS ACROSS ALL TREATMENTS

Parameter	Mean	Standard Deviation (SD)	Coefficient of Variation (CV %)
Survival Rate (%)	45.24	26.53	58.64
Number of Leaves	50.57	35.42	70.05
Number of Shoots	1.57	0.51	32.48
Average Shoot Length (cm)	29.66	26.42	89.05
Average Shoot Girth (mm)	5.33	0.7	13.1
Average Root Length (cm)	24.66	10.26	41.63
Average Root Volume (cc)	30.94	12.85	41.53

Note: High CV% (>40%) for most parameters indicates high treatment-induced variability.

The media ratio **2 cocopeat: 1 soil: 1 sand: 1 FYM (T-1)** resulted in the best overall vegetative growth. Cuttings in this medium achieved the highest average shoot length (72.66 cm), average shoot girth (6.29 mm), average root length (34.33 cm), and average root volume (48.33 cc). The survival rate for T-1 was 33.33%.

TABLE 2
EFFECT OF DIFFERENT GROWTH MEDIA ON THE VEGETATIVE GROWTH PARAMETERS OF KIWI HARDWOOD CUTTINGS

Treatment	Avg. Shoot Length (cm)	Avg. Shoot Girth (mm)	Avg. Root Length (cm)	Avg. Root Volume (cc)
T-1: 2Cocopeat:1Soil:1Sand:1FYM	72.66	6.29	34.33	48.33
T-2: 1C:1V:2Sd:1F:1S	4	4.3	8.5	10
T-3: 1P:1V:1C:1Sd:1S:2F	16.4	4.69	26	28
T-4: 2P:1V:1Sd:1F	24	5.08	22.87	32.14
T-5: 2V:1Sd:1F:1S	4	4.1	0.00*	0.00*
T-6: 2Sand:1Soil:1FYM	71	5.65	35.5	31.75
T-7: 1V:1P:1C:2S:1F:1Sd	76	6.06	25.66	45
T-8: 1Soil:1FYM:1Sand	35.3	5.07	34.3	36.6
T-9: Sand	7.5	4.61	22.25	37.5
T-10: FYM	34.6	6.01	18.3	43.33
T-11: Perlite	11	5.01	34	40
T-12: Vermiculite	9.14	6.29	21.14	36.42
T-13: Cocopeat	12.2	5.45	26.8	30
T-14: Soil	39.95	5.7	27.5	32.33
Mean	**29.66**	**5.33**	**24.66**	**30.94**

C: Cocopeat, V: Vermiculite, P: Perlite, S: Soil, F: FYM, Sd: Sand.
***** Callus formation only, no measurable roots.***

In contrast, the **highest survival rates** were observed in other media. **Pure vermiculite (T-12)** and **pure cocopeat (T-13)** both achieved 100% survival. The media blend **2 perlite: 1 vermiculite: 1 sand: 1 FYM (T-4)** also showed a very high survival rate of 93.33%. However, the cuttings in these high-survival media generally exhibited lower values for shoot and root growth parameters compared to T-1.

TABLE 3
EFFECT OF DIFFERENT GROWTH MEDIA ON SURVIVAL, LEAF COUNT, AND SHOOT NUMBER OF KIWI HARDWOOD CUTTINGS

Treatment	Survival Rate (%)	Total Number of Leaves	Avg. Number of Shoots
T-1	33.33	47	1
T-2	33.33	19	1
T-3	53.33	41	1.67
T-4	93.33	103	1.67
T-5	20	12	1
T-6	33.33	66	1.67
T-7	40	61	1.67
T-8	26.67	42	1.67
T-9	60	34	1.67
T-10	40	37	1.67
T-11	30	21	1.67
T-12	100	106	1.67
T-13	100	97	1.67
T-14	30	14	1
Mean	**45.24**	**50.57**	**1.5**

Some media combinations, such as T-2 and T-5, performed poorly, resulting in low survival and minimal growth, with T-5 showing only callus formation without root development.

IV. DISCUSSION

The results demonstrate a clear trade-off between achieving high cutting survival and promoting vigorous subsequent growth, mediated by the physical and chemical properties of the rooting medium.

The superior growth performance in the **2 cocopeat:1 soil:1 sand:1 FYM** blend can be attributed to its optimal balance. Cocopeat offers excellent moisture retention and aeration, FYM provides nutrients, sand ensures drainage, and soil adds structure. This creates an ideal environment for root development and shoot elongation, aligning with findings by Shylla et al. (2000) and Chandel and Chhukti (2013), who reported best results in mixed media.

Conversely, sterile, well-aerated single components like **vermiculite and cocopeat** minimized rot and promoted initial rooting, leading to exceptional survival rates. This supports the known importance of a disease-free, porous medium for cutting establishment. However, their lower nutrient content likely limited sustained vigorous growth without supplemental feeding, a factor noted in other studies on soilless media.

The significant effect of media on all parameters underscores its critical role. Our finding that a balanced blend promotes the most robust plants, while simpler media maximize survival, offers practical flexibility. Propagators can choose a medium based on their primary goal: using blended media like T-1 to produce field-ready plants in one season, or using high-survival media like T-12/T-13 to maximize plant numbers, potentially with a subsequent potting-up stage.

V. CONCLUSION

The expansion of the kiwifruit industry requires efficient propagation protocols. This study concludes that the growth medium significantly impacts the success of kiwi hardwood cutting propagation. For nursery entrepreneurs aiming to produce **vigorous, well-developed plants**, the media ratio **2 cocopeat: 1 soil: 1 sand: 1 FYM** is recommended. For those prioritizing the **maximization of plant establishment numbers**, **pure vermiculite or pure cocopeat** are highly effective. These findings provide scientifically supported, low-cost options utilizing readily available materials, contributing to the development of sustainable kiwi fruit nursery entrepreneurship in India's hill regions. Further research on the economic feasibility and long-term field performance of plants raised in these media is suggested

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Abundance of Weaver Ants (*Oecophylla smaragdina*) in Three Forest Stands

Musyafa

Faculty of Forestry Universitas Gadjah Mada Yogyakarta, Jln.Agro No.1 Bulak sumur Yogyakarta 55281
*Corresponding Author

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Abstract— *Weaver ants, Oecophylla smaragdina (Hymenoptera: Formicidae) are aggressive predators and consume various species of pests of agricultural and forest plants. The ants build nests and live in the trees. This research was done to know the percentage of trees colonized by weaver ants, individual number of weaver ants, and the number of nest of weaver ant on teak, eucalypt, and acacia stands and also the occurrence of trophobionts on these trees. The research was done in May, July and September 2015. The abundance of weaver ants was determined by counting the number of nests ~~and the individual number of weaver ants on the trees~~* ***as the primary measure of colony presence. Foraging activity near the ground was also estimated by counting ants on tree trunks up to 1 meter in height.*** *Trophobionts which were living on the trees were also observed. The results showed that the percentage of trees colonized by weaver ants was the highest in eucalypt stand (7.0-8.6 %) followed by teak stand (1.1-4.2%) and no weaver ant nest found in acacia stand. The highest individual numbers of ant* ***activity on trunks*** *was found in teak stand (2-38 individuals) followed by eucalypt stand (8-20 individuals) and no weaver ant found in acacia stand. The number of nest was 1.0-5.4 nests/ tree on teak stand, 1.8-4.2 nests/tree on eucalypt stand and 0 on acacia stand. On teak stands, a decline of weaver ants* ***nest*** *population occurred in September (dry season)****,*** *whereas on acacia stands, there were no* ***nests found in any season****. Weaver ants symbiotically coexisted with* ***trophobionts*** *of Coccidae and Pseudococcidae on teak stand. Meanwhile, trophobiont was not found on eucalypt stands. Weaver ants probably obtain sugar from extraforal nectar on young leaf of eucalypt.*

Keywords— Oecophylla smaragdina; biological control; plantation forestry; tree phenology; trophobiosis; host tree suitability.

I. INTRODUCTION

Weaver ants *O.smaragdina*, (Hymenoptera: Formicidae) build nests in the trees. These insects live in tropical areas in Asia and Africa, and the ants are not found in subtropical areas. Weaver ants are social insects that live in colonies which consist of queen, male and worker ants (Hodleber, 1983).The queen lays eggs and it usually has a bigger body size (15-16 mm), and her body is brownish green. The queen ant stays in the nest, which is hidden and located at the higher part of a tree. During rainy seasons, it is common for a colony to have several queens, because during the rainy season there is plenty of food available for the ants. Male ants mate with the queen ant and they only live for one week, and they die after one week. Worker ants are infertile females and these ants are responsible for caring for the young, the pupae and the queen. These worker ants are also responsible for collecting food, defending the nest, and transferring larvae and pupae (Kaleka and Haryadi, 2012).

Weaver ants go through a complete metamorphosis process. The life cycle of an ant colony begins when a mated queen finds a favorable location for its first nest among the leaves of a tree or a shrub; she lays around 35 eggs within 5-10 days after it breaks off its wings (Lokker, 1990).

The larvae undergo several skin changes before they develop into pupae (Kaleka and Haryadi, 2012). The final instar of larvae (15 days old) can produce silk which is used to cover the cavities in the nest (Lokker, 1990). By the age of 17 days, the larvae develop into pupae, and the first worker ants appear after 28 days (Lokker, 1990; Putranto, 2012).

There are two types of food consumed by weaver ants, honey that comes from Homoptera other insects. The honey is collected from Homoptera members, such as Coccidae, Stictococcidae, Pseudococcidae, Coccidadae, Aphididae, Margarodidae, and

Ciicadellidae. The relations between Homoptera and the ants are mutualistic, in which the ants receive food that is rich in sugar and amino acids; and the bugs receive protection from predators and parasites. Weaver ants are generalist predators; they feed on almost all species of arthropods that they find. The common taxa of insects consumed by weaver ants are Heteroptera, Coleoptera, Orthoptera, Blattodea, mantid, Diptera and Arachnida (Locker, 1990).

Weaver ants need food that contains protein, fat and carbohydrate or sugar. Protein is obtained from insects eaten by the ants, every time the ants find food, they will bring it into the nest (Kaleka and Haryadi, 2012). Weaver ants obtain sugar which comes from exudates secreted by insects and from flower nectars. The sugar liquid is used as energy source to build a new nest. Flower nectars are taken from plants such as *Hibiscus tiliceaus, Entada phaseoloides, Caesalpinia traceyi, Flagellaria indica dan Smilaxaustralis* (Bluthgen and Konrad, 2004). A research by Kartikasari (2013) shows that weaver ants prefer eucalypt trees as their hosts.

O. smaragdina has been used for biological pest control in orange plantations in the year 340 before Christ. On cacao plants, weaver ants can reduce the damage from capsid pest. Weaver ants are also effective in controlling Pseudococcidae pest. In Australia weaver ants are used to control pests that infest mango plants. In Asia, the use of ants as pest predators has been practiced for a long time and has been tested scientifically (Way & Kho; 1992). Weaver ants (*Oecophylla smaragdina*) are members of the ant family that prove to be the most effective predators in tropical area. Weaver ants can be the predators for more than 50 species of pests from 12 species of different plants (Way & Khoo, 1992). Weaver ants have been used for more than 1600 years in Vietnam and China to control pests on orange plants. Weaver ants are also effective to control pests that harm cashew plants in Papua New Guinea. These predators are also useful to control bagworm pest that attacks oil palm plantations.

In Indonesia weaver ants are not yet commonly used for pest control. Forest stands are often troubled by pests such as *Hyblaea puera* caterpillars on teak plants and *Hypsipill*a sp. shoot borer on mahogany plants. Information about the role of weaver ants as predators in the forest hasn't been available. In Wanagama Forest Gunung Kidul, Yogyakarta there are some forest stands such as teak stand, eucalypt stand and acacia stand. Weaver ant is potential predators of pest attacking these stands. Therefore it is necessary to evaluate the abundance of weaver ants in these stands. This research is expected to open the path towards using weaver ants for pest control on forest plants.

The objective of the research is to determine

1) The percentage of trees colonized by weaver ant and the abundance of weaver ants (individual numbers of weaver ants and the number of weaver ant nest on teak, eucalypt and acacia stands).

2) Trophobionts that are involved in symbiosis with weaver ants.

II. MATERIALS AND METHODS

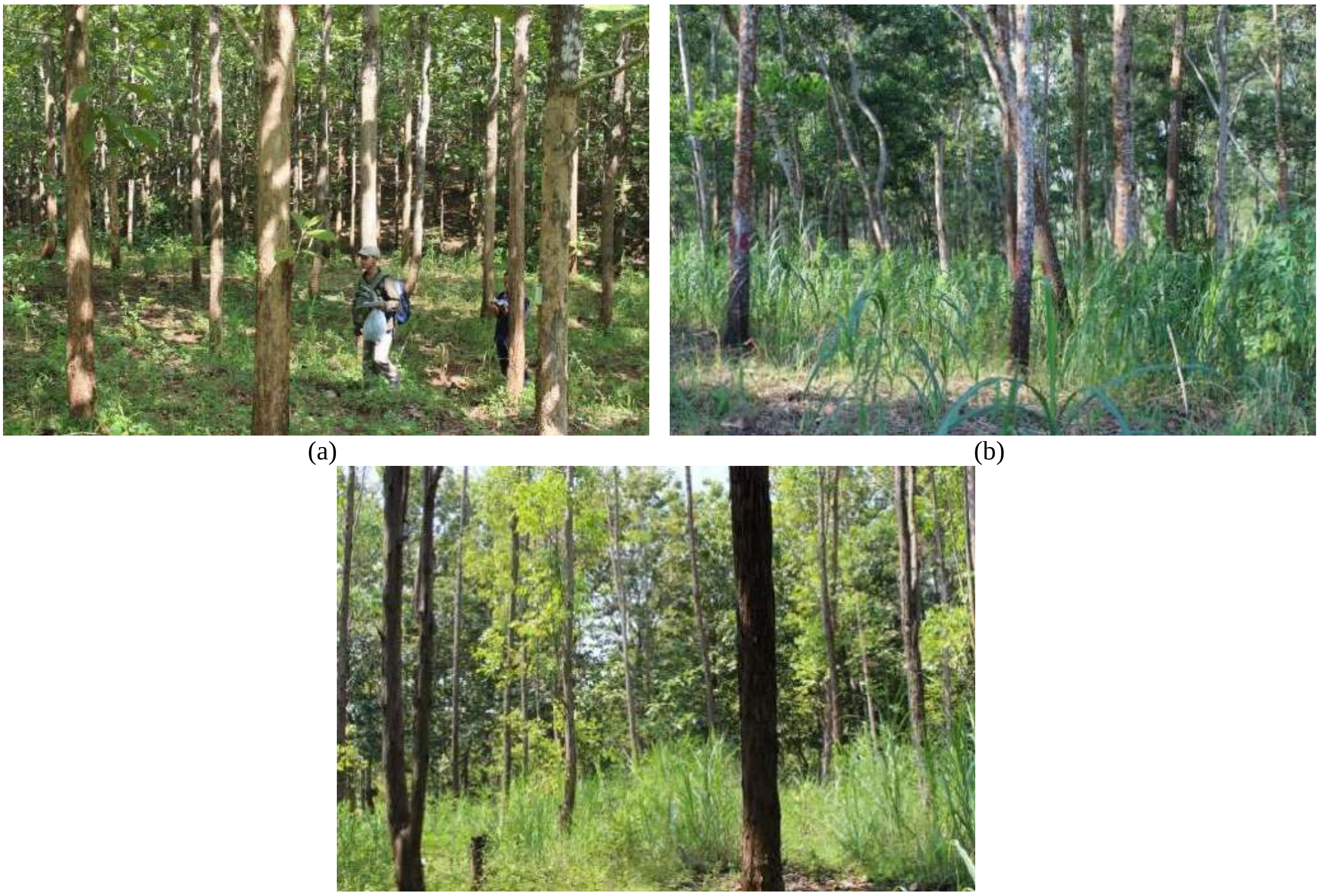
The research was conducted on teak (*Tectona grandis*), acacia (*Acacia mangium*), and eucalypt (*Eucalyptus pellita*) stands in May, July, and September 2015 in Wanagama Forest, Gunung Kidul, Yogyakarta.

2.1 Study Sites:

- **Teak stands:** The teak stands are located in plot 13; they are monoculture stands which were planted in 1990 in an area measuring 5 hectares. These stands have a rather dense crown, with a density of 1,060 trees/hectare. The teak plants have a diameter of 30.5 cm.

- **Eucalypt stands:** Eucalypt stands are located in plot 17 covering an area of 2.5 hectares. These plants are 35 years old, they have a density of 725 trees/hectare, and the diameter is 21.3 cm. The forest floor is full of grass which is regularly taken by the people around the forest to serve as forage for livestock. The eucalypt stands have a less dense crown, which lets more sunlight in.

- **Acacia stands:** The stands are located in plot 18 covering an area of 0.6 hectares. The plants are 25 years old, with a diameter of 19.7 cm. The density is 717 trees per hectare. The floor is full of grass, which is regularly taken by people who live around the forest to be used as forage for livestock; there are also Siam weed (*Chromolaena odorata*), peanut, *Lantana camara*, piper and *Streblus asper* plants. The acacia stands have a rather dense crown; therefore, the intrusion of sunlight is not too high, around 51%.



(a) (b)

(c)

FIGURE 1: Teak stand (a) acacia stand (b) and eucalypt stand (c) at Wanagama

2.2 Sampling Design:

A 20x20-meter measuring plot was established in the teak stand (10 replications), the eucalypt stand (8 replications), and the acacia stand (5 replications). The number of measuring plots was proportional to the area of each stand, with a sampling intensity of more than 5%. The distance between plots within a stand was 10 m.

2.3 Data Collection:

Within each plot, every tree was surveyed. For each tree, the diameter at breast height (DBH) was measured. The primary measure of weaver ant colony presence was the count of all visible nests in the tree canopy. As a supplementary index of ground-level foraging activity, the number of worker ants present on the tree trunk up to a height of 1 meter from the ground was counted. **This trunk count is an index of localized activity and is not a measure of total colony size.** A systematic visual search for trophobiont hemipterans (scale insects, mealybugs) was conducted on the trunk and major branches of all trees, with particular attention to those hosting ant nests or trails.

2.4 Data Presentation:

Data are presented descriptively as means and ranges. Trends between stands and across seasons are discussed qualitatively. Formal statistical comparison was limited by the low absolute number of colonized trees and the absence of colonies in acacia stands.

III. RESULTS AND DISCUSSION

3.1 Colonization and Nest Abundance:

The percentage of trees hosting weaver ant nests was highest in the eucalypt stand (7.0–8.6%), followed by the teak stand (1.1–4.2%). No weaver ant nests were found in the acacia stand during any sampling period (Figure 2). The mean number of nests per colonized tree was higher in teak (ranging from 1.0 to 5.4 nests/tree) than in eucalypt (1.8 to 4.2 nests/tree), though both showed considerable variation (Figure 3).

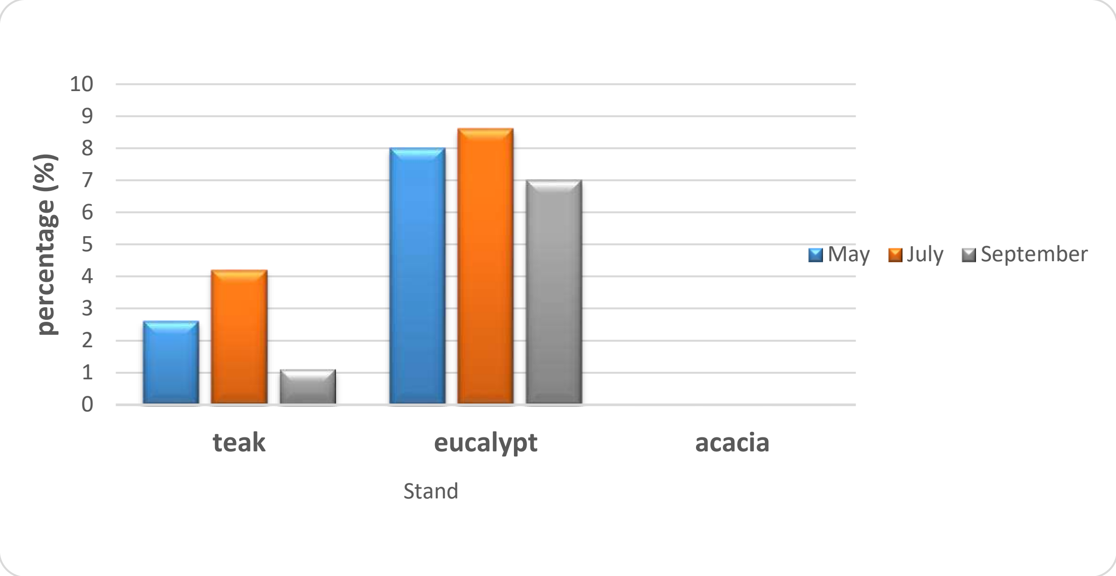


FIGURE 2: Percentage of teak, eucalypt and acacia tree that become weaver ant hosts

At the teak stand, the number of colonized trees and nests per tree declined in September (late dry season), coinciding with leaf senescence. In contrast, colony presence in the evergreen eucalypt stand remained stable across all months (Figures 2 & 3). The deciduous nature of teak likely creates a seasonal bottleneck, as leaf fall destroys nest sites and may reduce prey and carbohydrate availability. Eucalypt, with its persistent foliage and observed extrafloral nectar sources on young shoots (Figure 6), provides a more stable environment for colony maintenance.

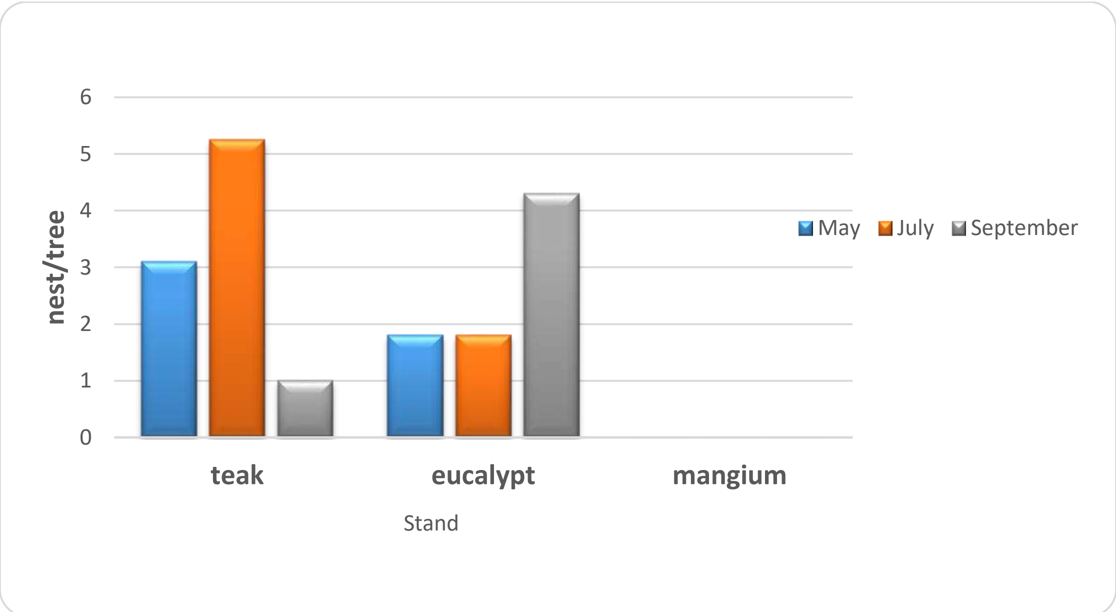


FIGURE 3: The number of weaver ant nests per tree on teak, eucalypt and acacia stands

3.2 Trunk Foraging Activity:

Counts of ants on the lower trunk (0-1 m height) varied between stands and seasons (Figure 4). The highest counts were recorded in teak in July (up to 38 individuals), followed by eucalypt. Activity declined in both stands by September. **It is crucial to interpret these counts as an index of ground-level foraging traffic, not as a census of colony size.** The observed patterns may reflect seasonal shifts in colony resource allocation or ground-based prey search, but the methodological limitation precludes definitive conclusions about total ant abundance. The concurrent decline in both trunk activity and nest counts in teak during September supports the interpretation of an overall seasonal contraction in colony activity.

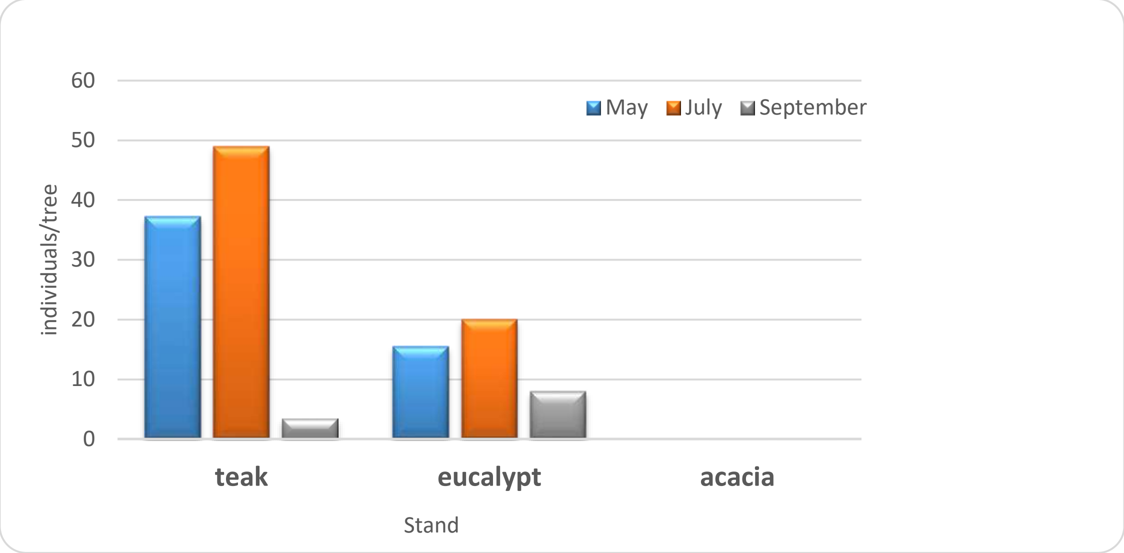


FIGURE 4: The number of individual weaver ants per tree (at the height of 1 m) on teak, eucalypt and acacia stands

3.3 Absence of Colonies in Acacia:

The complete absence of weaver ant nests in acacia stands was notable. This contrasts with other studies noting acacia as a potential host. Possible explanations observed or hypothesized in our study site include: (1) intensive collection of ant larvae ("kroto") for bird food, which may locally extirpate colonies, and (2) the presence of other ant species (e.g., *Pheidole* sp.) observed on acacia, which may compete with or disrupt founding *O. smaragdina* queens. The lack of both nests and trunk-foraging ants strongly suggests that acacia is not functioning as a host tree for weaver ants in this plantation context under current conditions.

3.4 Trophobiont Associations:

Trophobiont hemipterans of the families Coccidae and Pseudococcidae were found in association with weaver ant trails and nests on teak trees (Figure 5). This mutualistic relationship provides ants with carbohydrate-rich honeydew and provides the hemipterans with protection. No such trophobionts were found on eucalypt trees. On eucalypt, ants were frequently observed aggregating on young, expanding shoots (Figure 6), a behavior strongly indicative of harvesting extrafloral nectar (EFN). This suggests a flexible foraging strategy where ants obtain carbohydrates from tended hemipterans on teak and directly from plant EFN on eucalypt, highlighting the influence of host tree traits on ant symbiotic relationships.

FIGURE 5: Coccidae tropobion on the teak plant.

FIGURE 6: Weaver ants at the shoot of eucalypt plant to obtain nectars.

IV. STUDY LIMITATIONS AND FUTURE RESEARCH

This study provides a foundational survey of weaver ant presence. A key limitation is the method of counting ants only on the lower trunk, which precludes estimates of total colony size or arboreal activity. Furthermore, the low number of colonized trees limited detailed statistical analysis. Future studies should incorporate standardized whole-tree surveys to better estimate colony abundance and spatial distribution. Experimental work is also needed to test the hypotheses generated here, particularly regarding the absence of ants from acacia and the relative importance of extrafloral nectar versus honeydew in different stands.

V. CONCLUSION

Weaver ant (*Oecophylla smaragdina*) colony occurrence, as measured by nest presence, varied significantly among teak, eucalypt, and acacia plantation stands. Eucalypt supported the most consistent colonization, likely due to its evergreen foliage and extrafloral nectar sources. Colonies in deciduous teak declined during the dry season leaf-shedding period. No colonies were found in acacia, suggesting it is not a functional host in this system, possibly due to anthropogenic pressure or biotic competition. The ants exhibited a flexible trophic strategy, engaging in mutualism with trophobionts on teak while potentially exploiting direct plant resources on eucalypt. These findings underscore that host tree species identity and phenology are key determinants of weaver ant distribution in managed forests, with important implications for their potential role in conservation biological control.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Market Linkages and Pricing Dynamics for Leafy Vegetables: Farmer Experiences and Retailer Requirements in Western India

Vasava Dhruvilkumar Chandubhai

International Agri-Business Management Institute, Anand Agricultural University, Anand – 388110, India
Corresponding Author

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Abstract— *Leafy vegetables such as coriander, spinach, and mint play a vital role in nutrition and farmers' livelihoods in India. Farmers face challenges including unstable prices, dependence on intermediaries, and post-harvest losses, while retailers require consistent quality, volume, and traceability. This study explores sources of procurement, post-harvest handling practices, and constraints faced by farmers in Nenpur (Kheda) and Padra (Vadodara), Gujarat, alongside retailer perspectives from organized and unorganized markets.*

Data were collected from 60 farmers using semi-structured interviews and analyzed using the Problem Perceived Index (PPI) and Garrett's Ranking Technique. Results show that most farmers are smallholders with less than one acre under leafy vegetables and moderate annual incomes (Rs. 2–3 lakh). Mint is cultivated year-round, while spinach and coriander are seasonal. Although 78% of farmers are aware of grading and sorting, packaging mainly involves gunny bags, contributing to post-harvest losses. Primary constraints include pests, natural calamities, distant markets, and high transportation costs.

The study suggests that direct procurement through collection centers, training in post-harvest handling, and investment in cold-chain infrastructure can improve farmer incomes and meet retailer requirements.

Keywords— Leafy vegetables, Market linkages, Post-harvest handling, Farmer experiences, Retailer requirements, Gujarat.

I. INTRODUCTION

India's agricultural landscape is increasingly horticultural, with vegetables playing a pivotal role in ensuring food and nutritional diversity. Among these, leafy vegetables are particularly vital due to their short cropping cycle, high nutritional density, and potential for generating continuous income for small and marginal farmers. In the state of Gujarat, the cultivation of greens like coriander, spinach, and mint is widespread, catering to both local and urban markets.

Despite their importance, the supply chains for leafy vegetables are notoriously fragmented and inefficient. These commodities are highly perishable, with a shelf life often limited to a few days under ambient conditions, making them susceptible to significant post-harvest losses estimated between 8-25% nationally. Farmers, often operating on small landholdings, remain at the mercy of traditional *mandi* systems characterized by asymmetrical information, price volatility, and a high dependency on intermediaries who capture a substantial share of the consumer rupee. Conversely, the retail sector, encompassing both unorganized vendors and organized players (e.g., supermarkets, online platforms), is evolving towards a demand for standardized quality, assured supply, and food safety—requirements that traditional chains struggle to fulfill.

Previous research highlights this disconnect. Studies by Mangala & Chengappa (2008) and Singh & Singla (2011) underscore the potential of direct farmer-retailer linkages in improving farmgate prices. However, gaps persist in understanding the on-ground constraints from the farmer's perspective, particularly concerning specific post-harvest practices for leafy greens, and their alignment with retailer procurement models. This study aims to bridge this gap by addressing the following objectives:

1. To profile the socio-economic characteristics and cropping patterns of leafy vegetable farmers in selected districts of Gujarat.
2. To assess the awareness and adoption levels of post-harvest handling practices among these farmers.
3. To identify and rank the major production, marketing, and post-harvest constraints faced by them.
4. To analyze farmer awareness and willingness to participate in modern, direct procurement systems.
5. To provide policy and intervention recommendations for strengthening market linkages.

II. MATERIALS AND METHODS

2.1 Study Area and Sampling:

The research was conducted in two major leafy vegetable-producing clusters of Central Gujarat: Nenpur in Kheda district and Padra in Vadodara district. These locations were purposively selected due to their known commercial cultivation of coriander, spinach, and mint. A sample of 60 farmers (30 from each district) cultivating at least one of the target crops was selected for primary data collection. Given the lack of a definitive sampling frame, a non-probability **snowball sampling** technique was employed, where initial contact farmers helped identify other cultivators in the vicinity, ensuring access to the relevant population.

2.2 Data Collection:

Primary data were gathered through **pre-tested, semi-structured interviews** conducted in the local language between [Insert Data Collection Period, e.g., January-March 2023]. The schedule covered modules on socio-economic profile, cropping patterns, cost of cultivation, marketing channels, post-harvest practices, and perceived constraints. **Field observations** supplemented self-reported data, particularly for post-harvest handling. Secondary data were collated from district agricultural offices, published literature, and government reports to contextualize the findings.

2.3 Analytical Framework:

Data were analyzed using descriptive statistics and specialized ranking techniques:

- **Descriptive Statistics:** For presenting socio-economic profiles, awareness levels, and cropping patterns in frequency and percentage terms.
- **Problem Perceived Index (PPI):** Used to quantify the severity of various constraints. Farmers rated each problem on a Likert-type scale (e.g., 1=Not Severe to 5=Extremely Severe). PPI was calculated as: PPI = (Sum of individual scores for a problem / Maximum possible score) * 100.
- **Garrett's Ranking Technique:** Employed to convert qualitative rank orders (assigned by farmers to listed constraints) into quantitative scores. The per cent position of each rank was converted into a Garrett's table score, and the mean score for each constraint was calculated. The constraint with the highest mean score was assigned the first rank.

III. RESULTS AND DISCUSSION

3.1 Socio-Economic Profile of Sample Farmers:

As presented in Table 1, the farming community surveyed is predominantly middle-aged (68% above 40 years) with moderate levels of formal education (50% with secondary schooling). A critical finding is the prevalence of **smallholder farming**, with 75% of respondents operating on less than one hectare of land dedicated to leafy vegetables. This aligns with the national pattern of fragmented holdings in horticulture. The average annual income from leafy vegetables fell in the range of Rs. 2–3 lakh, indicating a moderate but vulnerable economic dependence on these crops.

TABLE 1
SOCIO-ECONOMIC CHARACTERISTICS OF SAMPLE FARMERS (N=60)

Parameter	Category	Frequency	Percentage (%)
Age	20–30	6	10
	30–40	13	22
	40–50	20	33
	50–60	21	35
Education	Primary	10	16.7
	Secondary	30	50
	Higher Secondary	20	33.3
Landholding (ha)	<1	45	75
	1–2	15	25

3.2 Cropping Patterns and Seasonal Availability:

Mint emerged as a **year-round crop** in both locations due to its hardy nature and continuous demand, primarily for chutney and culinary uses. Spinach cultivation was concentrated in the Rabi (winter) and Summer seasons, avoiding the heavy rains of Kharif. Coriander, more sensitive to climatic conditions, was predominantly a Rabi-season crop in Nenpur, while in Padra, some farmers extended its cultivation into summer under managed irrigation (Table 2). This seasonality creates supply fluctuations that challenge consistent retail procurement.

TABLE 2
SEASONAL AVAILABILITY OF LEAFY VEGETABLES IN STUDY AREAS

Vegetable	Nenpur (Kheda)	Padra (Vadodara)
Mint	Year-round	Year-round
Spinach	Rabi, Summer	Rabi, Summer
Coriander	Rabi	Rabi, Summer

3.3 Post-Harvest Handling Practices: The Awareness-Adoption Paradox:

A significant insight from the study is the gap between awareness and adoption of post-harvest practices. As shown in Table 3, while 78% of farmers were aware of concepts like grading, sorting, and packaging, the adoption rates were lower (65-75%). More critically, the **technology and materials used were rudimentary**. Grading and sorting were done manually by hand, a time-consuming process prone to inconsistency. Packaging was almost exclusively done in **gunny bags (jute sacks)**, which offer no protection against mechanical damage, moisture loss, or wilting, directly contributing to significant post-harvest losses during transportation. This practice persists despite known advancements in breathable plastic crates and modified atmosphere packaging for greens (Ali et al., 2022).

TABLE 3
AWARENESS AND ADOPTION OF POST-HARVEST PRACTICES

Practice	Awareness (%)	Adoption (%)	Material Used
Grading	78	75	Hand sorting
Sorting	78	70	Manual sorting
Packaging	78	65	Gunny bags

3.4 Ranking of Major Constraints:

The application of Garrett's Ranking Technique revealed the hierarchy of challenges (Table 4). **High transportation cost** emerged as the foremost constraint, a direct consequence of small, dispersed marketable surpluses making dedicated transport economically unviable. This was closely followed by **pest and disease attacks**, which affect yield and quality. **Distance to the primary wholesale market** ranked third, exacerbating transportation costs and time to market, thereby increasing perishability. The **lack of accessible cold storage** infrastructure ranked fourth, highlighting a critical bottleneck in the supply chain for preserving quality. **Price volatility**, often cited in literature, was acknowledged but ranked fifth, suggesting that immediate logistical and production challenges are more acutely perceived.

TABLE 4
RANKING OF MAJOR CONSTRAINTS FACED BY FARMERS (GARRETT'S RANKING)

Constraint	Mean Score	Rank
Transportation cost	82	1
Pest/disease attack	76	2
Market distance	70	3
Lack of cold storage	65	4
Price volatility	60	5

3.5 Market Linkages and Willingness for Change:

A promising finding was the high level of **awareness (78%)** among farmers about modern retail platforms like Bigbasket. Furthermore, **75% expressed willingness to supply directly** to such entities or through organized collection centers, provided assured prices and transparent weighing/payment systems were in place. This indicates a readiness to transition away from traditional channels if viable alternatives are presented.

IV. CONCLUSION AND RECOMMENDATIONS

This study confirms that the supply chain for leafy vegetables in Gujarat remains fraught with challenges that disadvantage smallholder farmers and fail to meet the quality consistency demands of a modernizing retail sector. The core issues are logistical (transport, distance), infrastructural (cold storage deficit), and practice-based (rudimentary post-harvest handling).

To bridge this gap, the following interventions are recommended:

1. **Promotion of Farmer Collectives and Collection Centers:** Facilitate the formation of Farmer Producer Organizations (FPOs) or strengthen existing ones. Establishing localized **primary collection and aggregation centers** at the village/cluster level can reduce transportation costs per unit, enable bulk marketing, and provide a direct interface for retailers.

2. **Targeted Capacity Building:** Extension programs must move beyond awareness to **skill development**. Hands-on training in proper harvesting at the right stage, pre-cooling techniques, and the use of low-cost improved packaging (e.g., perforated polyethylene bags, reusable plastic crates) is essential.

3. **Investment in Cool-Chain Infrastructure:** Public-private partnerships should be encouraged to establish **networked cool-chain facilities** (pack-houses with pre-cooling units, refrigerated vans) at strategic hubs. This can drastically reduce post-harvest losses and extend shelf-life.

4. **Facilitation of Direct Market Linkages:** State agricultural departments and FPO promoters should act as facilitators to create **structured tie-ups** between farmer groups and organized retailers/processors, ensuring fair pricing and contractual agreements.

Future research could focus on the economics of adopting improved post-harvest technologies and longitudinal studies on the impact of direct linkage models on farmer income resilience.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Analysis of the Determinants and Profitability of Maize Value Chain in Southeast Nigeria

Obasi, P. C.[1*]; Ahukaemere, M. C[2]; Nnorom, E. I.[3]

[1,3]Department of Agricultural Economics, Federal University of Technology Owerri, P. M. B. 1526 Owerri, Nigeria
[2]Department of Soil Science, Federal University of Technology Owerri, P. M. B. 1526 Owerri, Nigeria
*Corresponding Author

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Abstract— *The study analysed the determinants and profitability of maize value chain in Southeast, Nigeria. The study used primary data collected from four hundred and eighty (480) actors spread across Anambra and Ebonyi states of southeast, Nigeria. Data collection lasted from January 2025 to June 2025 and covered the 2023/2024 production season. The results of the study show that the average total revenue realized by maize seed suppliers, producers, processors and marketers respectively were ₦477,280.08, ₦3,420,276, ₦619,554.8 and ₦1,385,393.2 per ton with a total variable cost of ₦36,795.0, ₦228,777, ₦111,964 and ₦397,565 respectively and total fixed cost of ₦6,702, ₦18,890, ₦3,885.0 and ₦17,788 respectively. The maize actors made a net income of ₦433,783, ₦3,172,609 ₦503,705 and ₦970,040 respectively. The profitability index estimated are 9.97, 12.81, 4.35 and 2.34 respectively indicating that for every ₦1 invested by the respective actors yielded ₦9.97, ₦12.81, ₦4.35 and ₦2.34 to maize seed suppliers, producers, processors and marketers respectively. The results further show that maize seed producers contributed (2.03%) to the value chain while the marketers, seed suppliers and processors contributed (0.62%), (0.36%) and (0.33%) respectively. The determinants of maize seed supply are age, marital status, household size, educational level, years of experience, input cost, transportation cost, preservation and products costs, while gender, marital status, educational level, farm size, labour costs, input cost and product cost are the determinants of maize seed production. The determinants of maize seed processing are gender, age, household size, educational level, input cost and product cost while age, educational level, years of marketing experience, membership of marketing association, transportation cost, input cost and product cost are the determinants of maize seed marketing.*

Keywords— Determinants, Profitability, Maize, Value chain, Southeast, Nigeria.

I. INTRODUCTION

Maize as one of the most important cereal crops in the world is produced in a large quantity in Nigeria with the country as the tenth largest producer of the crop in Africa (IITA, 2012). Maize production in Nigeria is characterized by seasonality in production and lack of storage facilities. Due to the poor storage condition of maize in the area, prices fall during the peak production season thus resulting in low net returns to farmers. Despite being a staple crop with high local demand, the maize value chain in Southeast Nigeria suffers from low farm productivity, high post-harvest losses, weak processing and storage capacity, poor access to quality inputs and finance, and fragmented markets. Transportation of maize to the local markets is expensive due to poor road infrastructure in the area while packaging of maize in extended bags of 100kg has led to exploitation of farmers by traders. On the supply side, few local processors engage in meaningful value addition such as fortified flour, animal feed and starches thus leaving farmers to depend on market sales which are vulnerable to price swings. Market inefficiencies resulting from weak aggregation systems and limited market information constrain farmers' access to formal finance and insurance. Furthermore, institutional and policy gaps due to weak extension system, inconsistent input subsidy policy and limited public investment in storage facilities further exacerbate these problems. As a result of these, there is reduction in farmers' incomes and limitations in the region's capacity to supply value-added maize products. In view of the above, this study therefore seeks to:

1) Examine the socio-economic characteristics of maize value chain actors in the area,
2) Estimate the net margin and profitability of maize value chain in the area,
3) Evaluate the determinants of value addition of maize input suppliers, producers, processors and marketers in the study area.

This study was carried out covering the entire south-eastern states so as to fill the gap in knowledge observed when it was first executed in Imo state, Nigeria.

II. LITERATURE REVIEW

The value chain is defined as the full range of activities that firms and workers perform to bring a product from its conception to final use (Gereffi, 2011). It involves understanding all the different stages of manufacturing including intermediary phases under which a product goes through until it becomes a final product ready for consumption. It has its roots in the commodity chain concept and the world system approach which was conceived as a network of labour and production process whose end result is a finished commodity. The value chain approach to analysis allows one to understand how industries are organized by examining the structure and dynamics of different actors involved in that particular industry (Gereffi, 2011).

Maize is the fourth most consumed cereal during the past two decades, below sorghum, millet and rice (FAOSTAT, 2012). It is widely used in the preparation of traditional foods such as Pap, tuwo, gwate and donkunu, with the cereal cooked, roasted, fried, ground, pounded or crushed (IITA, 2012). IITA (2012) estimated that approximately 60% of maize produced in the country is used for industrial end uses for both human (flour, beer, malt drinks, cornflakes, starch, dextrose, syrup) and animal consumption, mainly poultry. This poses particular challenges to the capacity of the country to sustainably supply the volumes of maize needed by the consuming population. As a result of climate change, Ignaciuk and Mason-D'croz, D. (2014) estimated that maize prices could increase by up to 30% in the foreseeable future. However, there are some viable solutions that can be deployed to mitigate the challenges. While there are fewer opportunities for land expansion, there are significant avenues for improved maize germplasm and sustainable intensification to raise and stabilize yields and close yield gaps (Foley et al., 2011).

III. MATERIALS AND METHOD

3.1 The Study Area:

The study was carried out in southeast, Nigeria. Southeast geo-political zone comprises of Abia, Anambra, Ebonyi, Enugu and Imo states. The states in the area are basically agrarian. The area experiences two major climatic seasons, the rainy season which starts in March and ends in October and a four month dry season which lasts between November to February. The major food crops grown in the area are cassava, maize, yam, cocoyam, melon and different varieties of vegetables. The major economic activities include; farming, trading, food processing and craft making etc.

3.2 Method of Data Collection:

Multistage sampling technique was adopted in selecting the sample of 480 suppliers, producers, processors and marketers for the study. Two (2) states out of the five states that make up the area were purposively selected for the study because of the quantity of maize produced in these states. The states are Anambra and Ebonyi. In the first stage, 3 local government areas were randomly selected from each of the two states making a total of 6 local government areas. In the second stage, four communities were randomly selected from each of the 6 local government areas to make a total of 24 communities. In the third stage, 10 villages were randomly selected from each of the 24 communities earlier selected to give a total of 240 villages spread evenly across the two states which were used for the study. The sampling frame for the study comprised all the maize value chain actors in the villages. In the fourth stage, the sample was divided into 4 strata which comprised the value chain actors notably suppliers, producers, processors and marketers from each village. Random sampling technique was then used to select two (2) maize value chain actors from each village which gave a total of 480 respondents used for the study thus 120 suppliers, 120 producers, 120 processors and 120 marketers. Primary data were used for the study. The major instrument used for data collection was the questionnaire using handheld Garmin GPS-Map 64csx. The questionnaires were pretested in Abia state, Nigeria.

3.3 Method of Data Analysis:

The primary data collected were analysed using descriptive and inferential statistical tools. The net margin and profitability of maize input suppliers, producers, processors and marketers were achieved using the net income and profitability index model expressed as:

$$NIi = TR-TC \quad (1)$$

$$TCi = TVC+ TFC \quad (2)$$

Where,

NI = Net income (N/ha), TR = Total Revenue (N/ha)

TVC = Total variable cost (N/ha), TFC = Total fixed cost (N/ha)

TC = Total cost (N/ha)

The net income model was used for further measure of profitability of maize in the study area. The Profitability index model is expressed as:

$$PI = TR / TC \quad (3)$$

Where

PI= Profitability Index

Other variables remain as previously defined

The contributions of the major actors in the maize value chain in the area were achieved using the market share-ratio given as follows:

$$\text{Market Share (\%)} = (\text{Average Return per Actor} / \text{Total Return for all Actors}) \times 100 \quad (4)$$

The determinants of value addition of maize input suppliers, producers, processors and marketers were analysed using multiple regression analysis. The model is implicitly stated as:

$$Yi = f(X1, X2, X3, X4, X5, X6\ldots X15) +e \quad (5)$$

Yi = Value added (N)

X1 = Gender (dummy, 1= male, 0 = female)

X2 = Age (years)

X3 = Marital Status (dummy, 1 = single, 0 = married)

X4= Household Size (persons)

X5 = Educational Level (years spent in school)

X6 = Experience (number of years in business)

X7 = Membership of cooperative association (dummy, 1 = yes, 0 = otherwise)

X8 = price of maize seeds (N)

X9 = Product cost (N)

X10 = Labour cost (N)

X11 = Transport cost (N)

X12 = Processing cost (N)

X13 = Preservation cost (N)

e = random error

IV. RESULTS AND DISCUSSION

4.1 Socio-Economic Characteristics of Maize Value Chain Actors:

The distribution of maize value chain actors in southeast, Nigeria by socio-economic characteristics is presented in Table 1.

TABLE 1
DISTRIBUTION OF MAIZE VALUE CHAIN ACTORS BY SOCIO-ECONOMIC CHARACTERISTICS

Variables	Suppliers (%)	Producers (%)	Processors (%)	Marketers (%)
Gender				
Male	40	40	30	58
Female	60	60	70	42
Age				
15-29	5	10	20	15
30-44	10	20	35	30
45-59	55	50	40	45
60-74	30	20	5	10
Mean	45	42	36	38
Household size				
1-3	20	20	45	43
4-6	60	75	45	50
7-9	20	5	10	7
Mean	4	4	3	3
Educational level				
No education	5	5	7	6
1-6	25	35	10	4
7-12	44	30	56	50
13-18	26	30	27	40
Mean	7.6	7.3	8.3	9.3
Experience				
1-10	35	35	40	45
11-20	30	30	30	30
21-30	22	20	10	13
31-40	8	8	12	7
41-50	5	7	8	5
Mean	14	15	14	13
n	120	120	120	120

Source: Field Survey, 2025

Table 1 shows that majority (60%, 60% and 70%) of the respondents were female maize suppliers, producers and processors respectively. This result implies that females are more actively involved in maize seed supplies, production and processing than the males. That the females are more involved in these activities could be because maize seed supply, production and processing are believed to be female activities and less strenuous. The result is consistent with the findings of Eboiyehi (2006), Fodor (2006) and Joda (2010), Muhammed-Lawal et al. (2013) who observed that maize seed supplies, production and processing are predominantly female activities. Similarly, majority (58%) of the respondents are male maize seed marketers. This agrees with the findings of Ogunniyi and Omotesho (2011) who reported that maize marketing activities were carried out by males. Further analysis show that majority of the maize seed suppliers, producers, processors and marketers (55%, 50%, 40% and 45%) are within the age bracket of 45 and 59 years. The mean ages were 45, 42, 36 and 38 years respectively. This may suggest that the respondents were in their active and productive age during which they would be willing to engage in various risky economic activities that could enhance their income generation. This agrees with the findings of Amao et al.

(2007); Obasi et al. (2012; 2015) and Oluwasola (2010) who observed that younger household heads are more dynamic with regards to adoption of innovations.

Furthermore, (60%, 75%, 45% and 50%) of maize seed suppliers, producers, processors and marketers have household size within 4-6 persons. The mean household sizes were 4, 4, 3 and 3 persons for maize seed suppliers, producers, processors and marketers respectively. With respect to educational attainment, (44%, 30%, 56% and 50%) of the maize seed suppliers, producers, processors and marketers had secondary education, 25%, 35%, 10% and 4% had primary education while 26%, 30%, 27% and 40% had tertiary education respectively. However, 5%, 5%, 7% and 6% of the maize seed suppliers, producers, processors and marketers respectively had no formal education. The mean numbers of years spent in school were 7.6, 7.3, 8.3 and 9.3 respectively. This implies that majority of the respondents were literate and could adopt innovation. According to Ajao et al. (2012) the more educated farmers are, the higher their ability to utilize agricultural innovation. Finally, majority (35%, 35%, 40% and 45%) of the maize seed suppliers, producers, processors, and marketers respectively had between 1-10 years of experience. About 30%, 30%, 30% and 30% respectively had 11-20 years of experience. However, 22%, 20, 10% and 13% of the maize seed suppliers, producers, processors and marketers respectively had 21-30 years of experience. The mean years of experience were 14, 15, 14 and 13 for seed suppliers, producers, processors and marketers respectively. According to Amao et al. (2007) lengthy years of experience are an important requirement for the success of any business. The Findings of the study agrees with Dauda and Ndanitsa (2009) who observed that the length of years of experience of a working population in any occupation determines its performance in the competitive economic environment.

4.2 Net Margin and Profitability of Maize Value Chain Actors:

The costs and returns associated with maize seed suppliers, producers, processors and marketers are presented in Table 2. The net margin and profitability of the value chain actors were estimated from the table.

TABLE 2
COSTS AND RETURNS PER TON AMONG MAIZE VALUE CHAIN ACTORS (NAIRA)

Variables	Suppliers	Producers	Processors	Marketers
Average return	477,280.08	3,420,276	619,554.80	1,385,393.20
Depreciation	6702	18,890	3,885	17,788
Total fixed cost	6702	18,890	3,885	17,788
Product cost	8000	27,555	8,825	184,957
Preservation cost	12,698	-	-	-
Market levy	3,740	-	-	28,509
Cooking gas	-	-	22,658	-
Labour	-	76,810	24,333	-
Fertilizer	-	54,616	-	-
Pesticides	-	35,158	-	-
Fuel	-	-	19,847	29,748
Transportation	6,400	10,724	29,024	108,707
Packaging material	5,957	28,914	7,277	45,644
Total variable cost	**36,795**	**228,777**	**111,964**	**397,565**
Total cost	**43,497**	**247,667**	**115,849**	**415,353**
Gross Income	440,485	3,191,499	507,590	987,828
Net Income	**433,783**	**3,172,609**	**503,705**	**970,040**
Profitability index	**9.97**	**12.81**	**4.35**	**2.34**

Source: Field survey, 2025

The results in Table 2 show that the average total revenue realized by maize seed suppliers, producers, processors and marketers respectively were N477,280.08, N3,420,276, N619,554.8 and N1,385,393.2 per ton with a total variable cost of N36,795.0, N228,777, N111,964 and N397,565 respectively and total fixed cost of N6,702, N18,890, N3,885.0 and N17,788 respectively. The maize actors made a net income of N433,783, N3,172,609 N503,705 and N970,040 respectively. These figures suggest that the actors made profit from their investments. With regard to the profitability of the various enterprises by the actors, the profitability index estimated are 9.97, 12.81, 4.35 and 2.34 respectively indicating that for every N1 invested by the respective actors yielded N9.97, N12.81, N4.35 and N2.34 to maize seed suppliers, producers, processors and marketers respectively. This implies that maize seed supply and production are most profitable enterprises in the maize value in the area. However, marketing was found to be the least profitable enterprise in the maize value chain in the study area. The profitability index estimated for each enterprise measures the overall financial success of that enterprise among the maize value chain actors in the area. A ratio greater than one is preferable for any enterprise because the higher the ratio, the higher the profit.

4.3 Maize Value Chain Actors Market Share:

The maize value chain actors' market share is presented in Table 3.

TABLE 3

DISTRIBUTION OF MAIZE MARKET SHARE BY VALUE CHAIN ACTORS

Variables	Suppliers	Producers	Processors	Marketers
Total return per ton	134,462,064	168,077,580	190,487,924	224,103,440
Average return per ton	477,280.08	3,420,276	619,554.80	1,385,393.20
Market share (%)	0.355	2.03	0.325	0.62

Source: Field survey, 2025

Table 3 shows the results of the contributions of the major actors in the maize value chain in southeast, Nigeria. The findings show that maize seed producers contributed more (2.03%) to the market than any other sector of the value chain. This was followed by marketers (0.62%), seed suppliers (0.36%) and least by processors (0.33%). This suggests that the various actors can choose to move to maize production or any other activity to increase their income.

4.4 Determinants of Value Addition:

4.4.1 Determinants of value addition among maize input suppliers:

The result of the multiple regression analysis on the determinants of maize seed supply is presented in Table 4. The results show that the exponential functional form has eight significant variables with R2 of 0.798 while the semi-log functional form has nine significant variables with R2 of 0.864 respectively. Therefore, based on the magnitude of the coefficient of multiple determination (R2) and the number of statistically significant variables, the semi-log function was chosen as the lead equation and used for further analysis.

TABLE 4
RESULTS OF MULTIPLE REGRESSION ANALYSIS ON DETERMINANTS OF VALUE ADDITION AMONG MAIZE INPUT SUPPLIERS

Variable	Linear	Exponential	Semi-Log	Double-Log
Constant	-7808.503	2.333	-139061.459	-39.962
	(-1.538)	-0.742	(-4.615)	(-4.141)
Gender(X1)	-159.116	0.192	45.493	0.233
	(-0.190)	-0.371	-0.034	-0.54
Age(X2)	108.44	0.155	2302.849	5.959
	(2.745)***	(3.340)***	(2.356)**	(2.876)***
Marital status(X3)	-76.598	-1.328	6428.854	-1.452
	(-0.064)	(-1.780)**	(1.630)*	(-1.150)
Household size(X4)	-359.66	-0.34	2133.304	-0.346
	(-1.826)**	(-3.024)***	(1.713)**	(-0.694)
Education level(X5)	-99.351	-0.01	1075.188	-0.016
	(-0.810)	(-0.127)	(2.579)***	(-0.027)
Experience(X6)	93.396	0.049	180.508	0.17
	-1.258	-1.066	(2.165)**	-0.487
Association memb.(X7)	-181.608	-0.874	-7.547	-0.397
	(-0.223)	(-1.733)**	(-0.005)	(-0.873)
Input cost(X8)	-6.153	-0.008	7765.175	-1.441
	(-3.921)***	(-5.795)***	(4.355)***	(-2.525)***
Transport cost(X9)	-0.87	0.001	-1849.489	-0.046
	(-0.675)	(1.698)**	(-1.535)*	(-0.120)
Preservation cost(X10)	-0.85	-0.001	917.034	-0.158
	(-1.578)*	(-3.209)***	(2.661)***	(-1.434)
Product cost(X11)	1.073	0	12077.509	3.662
	(25.727)***	(10.405)***	(14.634)***	(13.857)***
R2	0.949	0.798	0.864	0.855
F-ratio	81.729	17.198	27.707	25.689
Standard error	2377.47291	1.47254	3895.32738	1.24731
n	120	120	120	120

******Significant at 1%, **Significant at 5% and *Significant at 10%***
Source: field survey, 2025

Age(X2) of maize seed suppliers was found to be positively related to net margin and statistically significant at 5% level. This implies that an increase in the age of the farmers will lead to an increase in net margin. This result disagrees with the findings of Martey et al. (2013) who observed a negative relationship between net margin and age of respondents in their study on performance and Constraints of Small Scale Enterprises in Accra Metropolitan Area of Ghana. Marital status(X3) of maize seed suppliers was found to be positively related to net margin and statistically significant at 10% level. Household size(X4) was also found to be positively related to net margin and statistically significant at 5% level. This implies that as farmers' household size increases, there would be a corresponding increase in net margin earned from maize seed supply. Education level(X5) was found to be positively related to net margin and statistically significant at 1% level. This implies that as the farmers acquire higher level of education, there will be an increase in their net margin. Education we know is the key that unlocks the potentials in people and leads to more prudent management of scarce resources. Furthermore, years of experience(X6) was found to be positively related to net margin and statistically significant at 5%. Similarly, input cost(X8) was found to be positively related to net margin and statistically significant at 1% level. This implies that as the cost of producing the maize seed increases, there will be a corresponding increase in the net margin of the enterprise. Transportation cost(X9) was found to be negatively related to net margin of input suppliers and statistically significant at 10% level. This implies that as the cost of transportation increases there will be a corresponding decrease in the net margin of the enterprise. Preservation cost(X10) and product cost(X11) were found to be positively related to net margin and statistically significant at 1% level respectively. This implies that as the cost of producing and preserving the maize seeds increases, there will be a corresponding increase in the net margin of the enterprise.

4.4.2 Determinants of value addition among maize Producers:

The result of the multiple regression analysis on the determinants of value addition among maize seed producers is presented in Table 5.

TABLE 5
RESULTS OF MULTIPLE REGRESSION ANALYSIS ON DETERMINANTS OF VALUE ADDITION AMONG MAIZE SEED PRODUCERS

Variable	Linear	Exponential	Semi-Log	Double-Log
Constant	-245539.572	4.671	-705044.256	-10.078
	(-1.686)	-0.667	(-0.453)	(-0.223)
Gender(X1)	-56275.367	-1.674	-52148.493	-1.528
	(-2.487)**	(-1.839)*	(-1.462)	(-1.784)*
Age(X2)	2712.648	0.067	173165.822	1.405
	-1.523	-0.788	-1.193	-0.334
Marital status(X3)	-13304.962	-0.831	-84542.905	-2.362
	(-2.550)**	(-0.715)	(-2.877)**	(-0.845)
Household size(X4)	8253.884	0.288	44230.566	1.38
	-1.031	-0.748	-0.872	(1.939)*
Education level(X5)	1223.686	0.102	-18209.24	0.264
	(2.597)**	(1.834)*	(-0.822)	-0.411
Experience(X6)	1101.96	0.059	27089.975	1.972
	-0.825	-0.925	-0.694	(2.743)***
Association memb.(X7)	29754.068	-0.67	40818.844	-0.739
	-1.173	(-0.549)	-1.023	(-0.638)
Farm size(X8)	34631.836	0.368	102790.307	0.561
	(4.007)***	-0.885	(3.959)***	-0.745
Labour cost(X9)	-4.611	0	-83155.445	-1.946
	(-2.571)***	-0.425	(-2.801)***	(-2.261)**
Fertilizer cost(X10)	11.699	0	-18214.864	0.796
	-0.54	-0.122	(-0.107)	-0.162
Transport cost(X11)	9.834	-0.001	13615.586	-0.495
	-0.801	(-1.088)	-0.558	(-0.699)
Input cost(X12)	5.066	0	-7904.466	0.548
	(2.933)**	-1.048	(-0.552)	(3.321)***
Product cost(X13)	0.82	9.18E-06	90730.229	1.68
n	(13.700)***	(3.192)***	(6.701)***	(4.279)***
R2	0.868	0.628	0.667	0.447
F-ratio	23.196	2.31	7.095	2.856
Standard error	81343.9324	3.91056	128982.216	3.73976
n	120	120	120	120

******Significant at 1%, **Significant at 5% and *Significant at 10%***
Source: field survey, 2025

Based on the number of variables statistically significant at 1% to 10% levels, the signs associated with the coefficients and the magnitude of the coefficient of multiple determination (R2), the linear function was chosen as the lead equation and used for further analysis of the data. Gender(X1) of the maize producers was found to be inversely related to net margin and statistically significant at 5% level. Gender in this study was used as a dummy variable. The result here implies that as more maize seed producers tend to be women, there will be a decrease in the net margin of the producers. Marital status(X3) of maize producers was found to be inversely related to net margin and statistically significant at 5% level. This implies that as more unmarried farmers engage in maize seed production, there will be a significant reduction in their net margin. This result agrees with the findings of Amao, Adesiyan and Salako (2007) who observed that high performance of married farmers could be attributed to fact that the spouses can serve as a form of labour by reducing the cost on hired labour and hence increasing the profit base of the enterprise. Similarly, Educational Level(X5) was found to be positively related to net margin and statistically significant at 5% level. This suggests that the more the farmers acquire higher levels of education, the higher the increase in the net margin. Farm Size(X8) of maize producers was found to be positively related to net margin and statistically significant at 1% level. This implies that an increase in farm size allotted for maize production will result to a significant increase in their net margin. Labour Cost(X9) was found to be negatively related to net margin and statistically significant at 1% level. This implies that as the cost of hired labour increases, there will be a corresponding decrease in the net margin of the enterprise. Input cost(X12) was found to be directly related to net margin and significant at 5% level. This may suggest that the more the farmers continue to use hybrid maize seeds which cost more, the higher will be the increase in the net margin of the farmers. Product cost(X13) was found to be directly related to net margin and statistically significant at 1% level. This implies that as the output of the maize producers' increases, there will be a corresponding increase in the net margin of the enterprise.

4.4.3 Determinants of value addition among maize Processors:

The result of the multiple regression analysis on the determinants of maize processing is presented in Table 6. The result shows that the linear and double log functional forms have six statistically significant variables each with R2 of 0.81 and 0.45 respectively. Based on the number of variables statistically significant at 1% to 10% levels, the signs associated with the coefficients and the magnitude of the coefficient of multiple determination (R2), the linear function was chosen as the lead equation and used for further analysis of the data.

Gender(X1) is positively related to net margin of the processors and statistically significant at 5% level. Gender in this study was used as a dummy variable. The result obtained here suggests that an increase in the number of males who engage in maize processing, the higher the increase in the net margin. Similarly, Age(X2) of maize processors was found to be directly related to net margin and statistically significant at 5% level. This suggests that an increase in the number of aged farmers who engage in maize processing, will lead to higher net margin. The result further shows that Household size(X4) is positively related to net margin and significant at 5% level suggesting that an increase in household size will increase the net margin of processors. Educational attainment(X5) was also found to be directly related to the net margin of processors and statistically significant at 1% level. This was expected on apriori because higher levels of education unlock potentials in people and enable them to learn new processing techniques including the use of modern processing machines. Input cost(X9) or raw maize seeds for processing was found to be negatively related to the net margin and statistically significant at 1% level. This implies that as the cost of maize seed for processing increases, there will be a corresponding decrease in the net margin of the enterprise. Finally, Product cost(X11) was found to be positively related to net margin and statistically significant at 1% level. This implies that as the output of the maize processors increases, there will be an increase in the net margin of the enterprise.

TABLE 6
RESULTS OF MULTIPLE REGRESSION ANALYSIS ON DETERMINANTS OF VALUE ADDITION AMONG MAIZE PROCESSORS

Variable	Linear	Exponential	Semi-Log	Double-Log
Constant	568.163	2.444	28382.65	5.413
	-0.123	-2.483	-1.112	-1.34
Gender(X1)	450.286	-0.55	-5055.939	-1.092
	(2.200)**	(-1.139)	(-1.421)	(-1.924)*
Age(X2)	269.764	-0.047	-25678.048	-2.82
	(2.214)**	(-1.817)*	(-1.449)	(-0.998)
Marital status(X3)	2928.783	0.623	13683.233	1.439
	-1.298	-1.289	-0.7	-0.461
Household size(X4)	308.675	0.06	-4306.07	-0.575
	(2.430)**	(2.394)**	(-2.404)**	(-1.938)**
Education level(X5)	54.081	-0.013	5.396	-0.056
	(3.288)***	(2.313)**	(2.701)**	(2.771)***
Experience(X6)	114.147	0.017	6276.649	0.989
	-0.556	-0.389	-1.144	-1.129
Association memb.(X7)	1610.743	0.611	5868.81	1.107
	-0.671	-1.19	-1.51	(1.784)*
Labour cost(X8)	-1.358	-0.001	-1040.197	-0.217
	(-0.718)	(-1.328)	(-0.588)	-0.771
Input cost(X9)	-1.345	0	-2649.845	-0.026
	(-6.531)***	(-3.208)***	(-3.889)***	(-3.055)***
Transport cost(X10)	-0.255	0	-486.952	-0.669
	(-0.316)	(-1.361)	(-0.151)	(-1.296)
Product cost(X11)	0.945	0	5287.969	0.693
	(11.795)***	(6.804)***	(4.081)***	(3.352)***
R2	0.808	0.647	0.462	0.448
F-ratio	18.406	7.986	3.74	3.541
Standard error	5749.38442	1.23018	9637.28289	1.53765
n	120	120	120	120

******Significant at 1%, **Significant at 5% and *Significant at 10%***
Source: field survey, 2025

4.4.4 Determinants of value addition among maize product marketers:

The result of the multiple regression analysis on the determinants of value addition among maize product marketers is presented in Table 7.

TABLE 7
RESULTS OF MULTIPLE REGRESSION ANALYSIS ON DETERMINANTS OF VALUE ADDITION AMONG MAIZE PRODUCT MARKETERS

Variable	Linear	Exponential	Semi-Log	Double-Log
Constant	-6229.071	2.035	-62988.825	2.312
	(-3.782)	-2.16	(-1.106)	-0.63
Gender(X1)	93.224	0.204	-4550.166	-0.065
	-0.271	-1.036	(-0.977)	(-0.218)
Age(X2)	-28.111	-0.039	29781.869	-2.149
	(-1.908)**	(-2.441)**	-0.805	(-1.902)*
Marital status(X3)	329.562	0.424	-19962.67	-0.042
	-0.479	-1.068	(-0.523)	(-0.017)
Household size(X4)	-3.03	0.065	4259.078	0.796
	(-0.018)	-0.688	-0.221	-0.641
Education level(X5)	283.931	-0.058	22414.68	0.446
	(2.854)***	(-1.015)	-0.607	-0.187
Experience(X6)	41.391	0.025	-3717.589	0.572
	(1.987)*	(1.929)*	(-1.845)*	(1.825)*
Association mem.(X7)	973.847	1.211	8907.774	1.436
	(2.330)**	(5.064)***	-1.506	(3.769)***
Transport cost(X8)	-1.601	0	-7584.993	-0.408
	(-8.910)***	(-2.642)***	(-1.984)**	(-1.658)
Input cost(X9)	-1.031	-2.47E-05	-12142.339	-0.646
	(-5.073)***	(-2.310)**	(-4.270)***	(-3.528)***
Product cost(X10)	1.009	6.22E-05	17656.991	1.362
	(4.079)***	(8.220)***	(5.264)***	(6.303)***
R2	0.998	0.889	0.579	0.745
F-ratio	2103.417	39.279	6.735	14.322
Standard error	1260.41028	0.7209	16966.99995	1.0929
n	120	120	120	120

******Significant at 1%, **Significant at 5% and *Significant at 10%***
Source: field survey, 2025

Based on the number of variables statistically significant within 1% to 10% levels, the signs associated with the coefficients as they aid in the economic interpretation of the results, and the magnitude of the coefficient of multiple determination (R2), the linear functional form was chosen as the lead equation and used for further analysis of the data. Age(X2) of maize product marketers was found to be inversely related to net margin and statistically significant at 5% level. This suggests that an increase in the number of aged farmers who engage in maize product marketing, will lead to a decrease in net margin. Educational level(X5) of the maize marketers was found to be directly related to net margin and statistically significant at 1% level. This implies that as the maize marketers advance in their educational level, there will be a significant increase in their net margin. Years of marketing experience(X6) was found to be directly related to net margin and statistically significant at 10% level. This implies that as the marketers acquire more years of experience in maize product marketing, there will be an increase in their net margin. This could be due to the awareness of innovative ideas and strategies in product packaging and advertising which result in higher volume of sales and higher net margin. Association membership (X7), was also found to be directly related to net margin and significant at 5% level. Transportation Cost(X8) was found to be inversely related to net margin and statistically significant at 1% level. This implies that as the cost of transporting goods from one market to another increase there will be a corresponding decrease in the net margin of the enterprise. Input cost(X9) was found to be inversely related to net margin and statistically significant at 1% level. This implies that as the cost of the various maize product increases there will be a corresponding decrease in net margin of the enterprise. Finally, product price(X10) was found to be directly related to net margin and statistically significant at 1% level. This implies that as product prices of the maize marketers increase there will be a corresponding increase in net margin of the enterprise.

V. CONCLUSION

The study analysed the determinants and profitability of the maize value chain in Southeast Nigeria. Key findings indicate that maize production is the most profitable segment (Profitability Index = 12.81), while marketing is the least profitable (PI = 2.34) due to high transportation and packaging costs. Producers also contributed the largest share (2.03%) to the chain's total value. The determinants of profitability vary across actor groups but consistently highlight the significant negative impact of transportation and input costs, and the positive role of education, experience, and cooperative membership. These findings underscore the need for targeted interventions, such as improved rural infrastructure, input subsidy programs, and the promotion of farmer cooperatives, to enhance efficiency and profitability across the maize value chain in Southeast Nigeria.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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The Role of Artificial Intelligence in Advancing Horticultural Crop Production

Dr. Sidhartha Kar

Scientist (Horticulture), KrishiVigyan Kendra, Malkangiri, Odisha University of Agriculture & Technology **(OUAT)**, Bhubaneswar, Odisha, India

*Corresponding Author

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Abstract— *Horticulture is fundamental to India's nutritional security and rural livelihoods, offering high income per unit area and year-round employment. However, the productivity of delicate horticultural crops—fruits, vegetables, spices, and flowers—is highly susceptible to biotic and abiotic stresses, as well as market volatility. Artificial Intelligence (AI) has emerged as a transformative decision-support system to address these precision-dependent challenges. This article delineates the practical applications of AI in horticulture, drawing from field experience. AI mechanisms facilitate early disease and pest detection through image recognition, optimize irrigation and nutrient management via sensor networks and predictive models, and enhance risk mitigation with hyperlocal weather forecasting. Furthermore, AI-driven robotics automate harvesting and grading, while machine learning algorithms aid in smart crop planning and market prediction. In protected cultivation and supply chain management, AI systems ensure optimal growing conditions and reduce post-harvest losses. Evidence from demonstration plots indicates that AI adoption leads to healthier crops, significant resource savings, reduced wastage, and higher farmgate returns. Conclusively, AI acts as an intelligent partner that empowers farmers rather than replaces them. With continued institutional support and training through frameworks like the Digital Agriculture Mission, AI is poised to make Indian horticulture more resilient, productive, and profitable.*

Keywords—Artificial Intelligence, Precision Horticulture, Smart Farming, Disease Detection, Predictive Analytics, Agricultural Robotics, Supply Chain Management.

I. INTRODUCTION

Horticulture is a cornerstone of India's agrarian economy, critical for strengthening nutritional security and improving rural livelihoods. Fruits, vegetables, spices, plantation crops, and flowers generate higher income per unit area and provide sustained employment throughout the year. Despite its economic significance, horticulture faces persistent challenges. The crops are inherently delicate and highly sensitive to water stress, pest and disease outbreaks, nutrient imbalances, and market fluctuations. Farmers often struggle with timely intervention as problems can appear suddenly and spread rapidly, leading to significant pre- and post-harvest losses.

In this context, Artificial Intelligence (AI) has emerged as a practical and reliable suite of technologies to augment human decision-making. AI is not a monolithic tool but a convergence of machine learning (ML), computer vision, Internet of Things (IoT) sensors, robotics, and advanced data analytics. Together, these technologies enable continuous, granular monitoring of crops, accurate diagnosis of plant needs, and timely, precise responses. Positioned not as a replacement for farmers but as an intelligent partner, AI supports nuanced, data-driven decisions in everyday farming. This article synthesizes field experience and scientific understanding to elucidate how AI is pragmatically improving horticultural crop production across India.

II. AI ACROSS AGRICULTURAL PLATFORMS

2.1 AI for Early Disease and Pest Detection:

A substantial proportion of horticultural losses stems from delayed identification of pests and diseases. AI-based solutions, primarily leveraging **computer vision and deep learning models like Convolutional Neural Networks (CNNs)**, have revolutionized this domain. Mobile applications allow farmers to photograph a symptomatic leaf, fruit, or stem for instant analysis. These tools compare the image against vast, curated datasets to provide a diagnosis and often a management recommendation within seconds. Initiatives by Krishi Vigyan Kendras (KVKs) and line departments are promoting the use of such apps among growers in tribal belts, including Malkangiri, with promising results.

TABLE 1
AI-ENABLED TOOLS FOR CROP HEALTH MONITORING

Tool/Platform	Primary Function	Key Benefit
Mobile Apps (e.g., Plantix)	Image-based diagnosis of diseases, pests, and nutrient deficiencies.	Enables rapid, in-field identification, preventing crop loss through timely action.
Drone-Based Scouting	Multispectral imaging to identify pest/disease hotspots and stress zones across large orchards.	Reduces blanket pesticide use and lowers scouting labour costs.
Automated Leaf Scanners	High-throughput, AI-powered analysis for detecting viral, fungal, and bacterial pathologies.	Improves accuracy and consistency of diagnosis, eliminating observer fatigue.

In high-value crops like banana, papaya, pomegranate, brinjal, chilies, and tomato, studies suggest that AI-driven early detection can potentially mitigate 20–40% of yield loss.

FIGURE 1: AI for Early Disease and Pest Detection

2.2 AI-based Irrigation Management:

Precision watering is paramount in horticulture, where both water deficit and excess adversely affect yield and quality. AI-based **smart irrigation systems** integrate real-time data from in-situ soil moisture sensors, evapotranspiration models, and weather forecasts to compute exact crop water requirements. These systems can autonomously control drip or micro-sprinkler networks, applying water only when and where needed.

Documented benefits from field implementations include:

- **Water Savings:** 25–50% reduction in water usage compared to conventional scheduling.
- **Labour Efficiency:** Minimizes manual intervention for irrigation operations.
- **Improved Yield Quality:** Promotes better fruit size, uniformity, and overall plant health.
- **Disease Reduction:** Lower incidence of soil- and moisture-borne fungal diseases.

This technology is particularly beneficial for water-intensive orchards (mango, guava, grape) and high-value vegetables (tomato, brinjal, cucurbits) grown under drip irrigation.

FIGURE 2: AI-based Irrigation Management

2.3 AI for Weather Forecasting and Risk Management:

Weather variability remains a primary source of uncertainty. AI models, particularly those using **Long Short-Term Memory (LSTM) networks**, analyze decades of historical climate data alongside real-time satellite and weather station inputs to generate hyperlocal, short-to-medium-term forecasts with superior accuracy. These forecasts power actionable alerts, enabling farmers to proactively manage risks.

AI-based advisories help farmers to:

- Adjust irrigation schedules proactively during predicted heat stress.
- Deploy protective measures (e.g., shade nets, anti-frost sprays) ahead of adverse events.
- Apply preventive plant protection sprays based on disease forecast models (e.g., for fungal outbreaks in Banana and Papaya).
- Optimize harvest timing to avoid periods of predicted rainfall or high humidity.

2.4 AI in Soil and Nutrient Management:

Soil health is the foundation of crop quality, productivity, and shelf-life. AI is making soil and plant-tissue testing more rapid and accessible. Portable spectrophotometers, coupled with AI algorithms, can provide instant nutrient estimates. Furthermore, image-based AI models can detect visual symptoms of nutrient deficiencies (e.g., nitrogen, potassium, magnesium, iron) often missed by the naked eye.

TABLE 2
AI APPLICATIONS IN SOIL AND NUTRIENT MANAGEMENT

AI Technology	Application	Impact
Portable Soil Sensors	Instant estimation of key soil parameters (N, P, K, pH, OC).	Facilitates precise fertilizer application, correcting imbalances.
AI-Powered Fertigation Units	Integration with drip irrigation to deliver dynamic, dose-specific nutrient solutions.	Promotes uniform growth and enhances nutrient use efficiency.
Foliar Image Analysis	Detection of visual symptoms of micronutrient deficiencies.	Enables timely correction, improving fruit colour, taste, and marketable yield.

These tools are invaluable for addressing subtle micronutrient disorders in citrus, papaya, and greenhouse vegetables.

2.5 AI-Enabled Robotics for Harvesting and Grading:

Harvesting is labour-intensive, costly, and seasonal. AI-enabled **agricultural robots** are being developed to identify ripe produce using computer vision to assess colour, size, shape, and even spectral signatures. While large-scale adoption in India is nascent, robotic harvesting is operational internationally for crops like strawberries, tomatoes, and apples.

Simultaneously, AI-based **automated grading and sorting lines** use similar vision systems to classify produce by size, colour, weight, and external defects with superhuman consistency. This improves product uniformity, fetches better prices in export markets (e.g., for mango, grape, pomegranate), and enhances competitiveness even in domestic markets.

2.6 AI for Smart Crop Planning and Market Prediction:

Crop selection and market timing are critical yet difficult decisions. AI models analyze vast datasets—including historical market arrivals, price trends, consumer demand patterns, weather forecasts, and transportation logistics—to generate predictive insights. This empowers farmers and FPOs (Farmer Producer Organisations) to make informed choices.

Key benefits encompass:

- **Informed Crop Selection:** Choosing crops with higher predicted profitability and lower market risk.
- **Optimized Nursery Scheduling:** Aligning seedling production with optimal planting windows.
- **Enhanced Market Returns:** Identifying favourable sales periods to avoid price gluts.
- **Reduced Wastage:** Better planning for highly perishable crops.

This application is especially impactful for crops with high price volatility, such as tomato, onion, capsicum, and marigold.

2.7 AI in Protected Cultivation Systems:

Greenhouses and shade-net houses represent controlled environments where AI can deliver maximal value. **AI-controlled environmental management systems** continuously monitor and automatically regulate parameters like temperature, humidity, CO_2 concentration, irrigation, and nutrient dosing via IoT actuators. This minimizes human error and maintains optimal growing conditions 24/7.

Such precision environments are ideal for high-value crops like capsicum, cucumber, strawberry, broccoli, orchid, and gerbera, leading to superior quality, reduced pest incidence, and maximized off-season yield and profits.

2.8 AI in Supply Chain and Quality Management:

Post-harvest losses in Indian horticulture are estimated at 20-30%. AI mitigates these losses by enabling smarter supply chains. **IoT sensors** monitor real-time temperature and humidity during storage and transit. **Machine learning models** predict remaining shelf-life based on product physiology and handling conditions. Furthermore, computer vision can detect early signs of spoilage, and blockchain-integrated systems ensure traceability from farm to fork, which is crucial for export compliance and brand assurance.

III. FIELD EXPERIENCE, CHALLENGES, AND OBSERVATIONS

Demonstration plots in Malkangiri district have facilitated the introduction of AI-based mobile apps for disease diagnosis. Farmers grappling with chili leaf curl virus or brinjal fruit and shoot borer have successfully implemented timely, targeted interventions based on AI advice. Preliminary observations indicate improvements in both yield quantity and quality, coupled with a reduction in unnecessary pesticide expenditure, lowering production costs and environmental impact.

These field experiences affirm AI's practicality beyond laboratory settings. However, challenges to widespread adoption persist and must be acknowledged:

- **High Initial Investment:** Cost of sensors, hardware, and software.
- **Digital Infrastructure:** Dependence on reliable electricity and internet connectivity.
- **Farmer Capacity Building:** Need for continuous training to build digital literacy and trust.

- **Localized Model Training:** AI algorithms require large, locally-relevant datasets to be accurate across India's diverse agro-climatic zones.

Figure 3: Practical Observations

IV. CONCLUSION

Artificial Intelligence is steadily transitioning from a novel concept to an integral component of precision horticulture. Its core value lies in its capacity for continuous monitoring, processing complex, multi-layered data, and providing actionable, timely intelligence. For a sector where precision directly dictates quality and profitability, AI is fundamentally transformative. It empowers farmers to detect threats early, conserve vital resources like water and fertilizers, mitigate climate risks, and secure better market returns. Crucially, AI is an empowering tool for farmers, not a replacement for their expertise. With sustained policy support (e.g., Digital Agriculture Mission 2021–2025), institutional training through KVKs, and focused efforts to overcome adoption barriers, AI can catalyze a future where Indian horticulture is more resilient, productive, sustainable, and profitable.

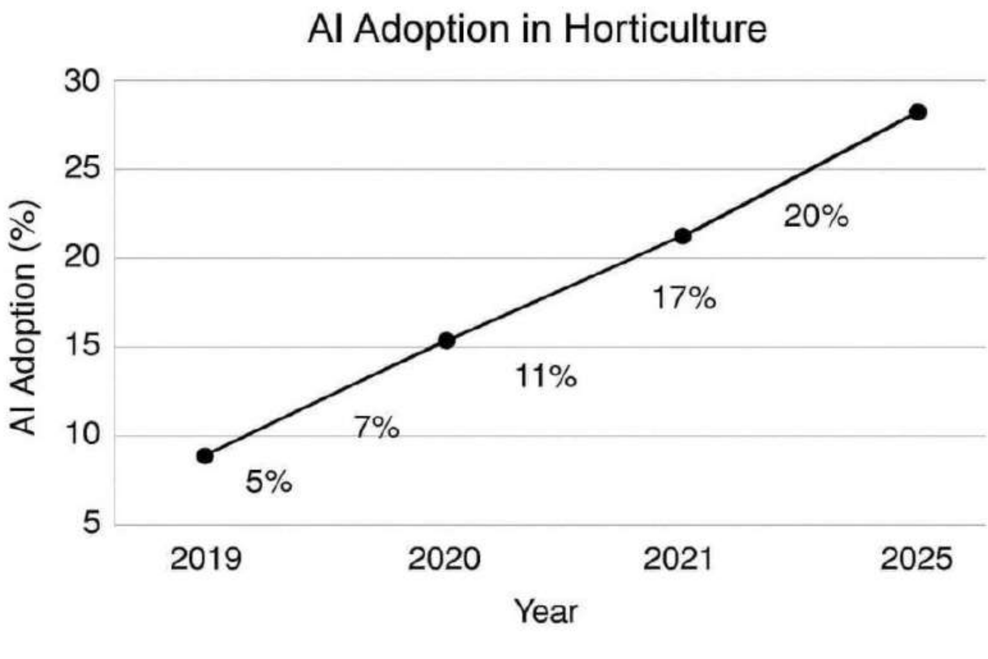

FIGURE 4: AI Adoption in Horticulture year wise

TABLE 3
APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN HORTICULTURAL CROP PRODUCTION

AI Application Area	Specific Tools / Technologies	Purpose / Function	Benefits to Farmers / Horticulture Sector
Crop Monitoring & Health Diagnosis	Image recognition, CNN models, drones, mobile-based disease scanners	Early detection of pests, nutrient deficiency, diseases	Reduced crop loss, timely intervention, lower pesticide use
Precision Irrigation	IoT soil-moisture sensors, AI-based irrigation scheduling	Determines exact water requirement	Saves water, improves fruit/vegetable quality
Yield Prediction	Machine learning models (Random Forest, ANN)	Forecast yield based on weather, soil	Better planning for market, storage, labor
Weather-based Advisory Systems	AI-driven climate models, predictive analytics	Forecast rainfall, temperature, humidity	Helps farmers avoid climate-related damage
Smart Fertilizer Management	Sensor networks, nutrient-mapping AI systems	Recommends precise fertilizer dose	Reduces nutrient wastage, increases returns
Automated Grading & Sorting	Computer vision, conveyor-based AI scanners	Classifies fruits/vegetables by size, color, defects	Faster processing, higher market price, standardization
Robotics in Horticulture	AI-powered harvesters, weed-removal robots	Automates harvesting, pruning, weeding	Reduces labor shortage issues, increases efficiency
Supply Chain Management	AI logistics platforms	Predicts market demand	Improved yield management and profitability

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Biosensors for Non-Destructive Fruit Quality Assessment: A Comprehensive Review of Principles and Applications in Green Horticulture

Jadala Shankaraswamy[1*]; Aggiri Mamatha[2]

Department of Fruit Science, College of Horticulture, Mojerla, Sri Konda Laxman Telangana Horticultural University, Wanaparthy-509382, Telangana, India
*Corresponding Author

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Abstract— *Biosensors are analytical devices that combine a biological sensing element (enzymes, antibodies, microorganisms, DNA, or plant tissues) with a physical transducer to detect and measure specific substances (analytes) in fruits. This interaction produces a measurable biological response that the transducer converts into an electrical, optical, or thermal signal. Valued for assessing fruit quality, biosensors enable rapid, real-time, and non-destructive testing, overcoming the time-consuming, destructive nature of traditional laboratory analysis. An effective biosensor exhibits high selectivity (detecting only the target in complex tissues), sensitivity (detecting trace compounds), quick response, linearity, reproducibility, and stability.*

Different biosensor types operate on distinct sensing principles. Electrochemical biosensors measure electrical signals from biochemical reactions, offering low cost and fast response. Optical biosensors detect changes in light (absorption, fluorescence) for color and biochemical analysis. Calorimetric biosensors measure minute heat changes from reactions, while piezoelectric/acoustic sensors detect mass-based vibrations on crystal surfaces. Potentiometric biosensors measure voltage changes for ion detection (e.g., pH), and amperometric biosensors measure current changes for detecting pesticides and sugars.

In fruit quality assessment, advanced biosensing technologies are widely applied. Optical sensors like Near-Infrared Spectroscopy (NIRS), hyperspectral imaging, and visible light imaging monitor ripeness, defects, sugar levels, and maturity by analyzing light absorption/reflection. Electromagnetic technologies such as Nuclear Magnetic Resonance (NMR) and Terahertz sensing reveal internal structures, moisture, and residues non-destructively. Acoustic/ultrasonic sensors use wave propagation to determine firmness and internal defects. Electronic nose (E-nose) systems detect volatile compounds to assess aroma, freshness, and spoilage. Dielectric property sensors measure electrical permittivity to assess internal quality and moisture content. This review comprehensively details the principles, types, and integrated applications of these biosensors for non-destructive fruit quality monitoring in green horticulture.

Keywords— Fruit quality; biosensors; non-destructive sensing; NIR spectroscopy; hyperspectral imaging; dielectric sensing; E-nose; firmness; SSC; VOCs; postharvest monitoring.

I. INTRODUCTION

Biosensors are advanced analytical tools that combine biological sensing elements—such as enzymes, antibodies, or microorganisms—with physicochemical transducers to detect specific analytes. These devices translate biological interactions into measurable signals like electrical current, light intensity, or heat changes, offering rapid, sensitive and selective detection. Originally developed for medical diagnostics, biosensors have found expanding applications in agriculture, food safety, and environmental monitoring due to their portability, cost-effectiveness and real-time capabilities.

In the horticultural sector, biosensors are revolutionizing fruit quality assessment by enabling non-destructive, precise and continuous monitoring of key parameters. Traditional methods for evaluating fruit quality—such as chemical assays or manual inspection—are often time-consuming, labour-intensive, and destructive. Biosensors overcome these limitations by providing instant feedback on attributes like ripeness, sweetness, acidity, firmness, aroma and nutritional content. This empowers farmers, processors, and retailers to make informed decisions about harvest timing, storage conditions and market readiness.

Fruit quality is a multifaceted concept involving physical appearance, internal composition, taste and shelf life. Biosensors can detect chemical markers such as glucose, ethylene, citric acid and polyphenols, which correlate with ripeness, flavour and antioxidant levels. Mechanical sensors assess firmness and texture, while optical and electronic nose technologies evaluate colour, aroma and spoilage. These insights are crucial for maintaining consumer satisfaction, reducing post-harvest losses and ensuring food safety across the supply chain.

As biosensor technology evolves, integration with IoT and AI systems is paving the way for smart farming solutions. Portable and wireless biosensors can transmit real-time data to cloud platforms, enabling predictive analytics and automated decision-making. This not only enhances productivity and sustainability but also supports traceability and compliance with quality standards. This review provides a comprehensive analysis of biosensor principles, types, and integrated sensing technologies for fruit quality assessment, concluding with future perspectives on their role in precision horticulture.

II. FUNDAMENTALS F BIOSENSORS FOR HORTICULTURE

2.1 Mechanism of Biosensors:

The mechanism of a biosensor is a multi-step process that begins with the biological recognition element, which serves as the heart of the device. This component is carefully selected based on its ability to interact specifically and selectively with the target analyte—such as glucose, ethylene, citric acid, or pesticide molecules. Depending on the biosensor type, this interaction may involve enzymatic catalysis, antibody-antigen binding, nucleic acid hybridization, or microbial metabolism. For example, in an enzyme-based biosensor, the enzyme catalyzes a reaction with the analyte, producing a product that can be detected. In immunosensors, antibodies bind to specific antigens, triggering a measurable change. These biological interactions are highly specific, ensuring that the biosensor responds only to the intended substance even in complex mixtures like fruit pulp or juice.

Once the biological interaction occurs, the transducer plays a critical role in converting the biochemical event into a physical signal. This signal can take various forms depending on the transduction method used. Electrochemical transducers measure changes in current, voltage or impedance resulting from the reaction. Optical transducers detect variations in light absorption, fluorescence, or refractive index. Calorimetric transducers monitor heat changes during exothermic or endothermic reactions, while piezoelectric transducers sense mass changes through shifts in vibration frequency. Each transduction method offers unique advantages in terms of sensitivity, speed, and suitability for different analytes. For instance, amperometric sensors are ideal for detecting small molecules like glucose or ascorbic acid, while piezoelectric sensors excel in measuring physical changes such as fruit firmness.

The final stage involves signal processing and output display, where the raw signal is amplified, filtered, and translated into a readable format—such as a digital value, graph or alert. This enables real-time monitoring and decision-making, which is especially valuable in agricultural settings. In fruit quality assessment, biosensors can be integrated into handheld devices or smart packaging systems to continuously track ripeness, freshness and contamination. The ability to detect multiple analytes simultaneously—such as sugars, acids and VOCs—makes biosensors indispensable for holistic quality evaluation.

2.2 Essential Characteristics of Biosensors:

Biosensors have emerged as transformative tools in horticulture, offering a rapid, non-destructive, and highly specific means of evaluating fruit quality. Their performance in such applications is governed by six fundamental characteristics: selectivity, sensitivity, linearity, response time, reproducibility, and stability. Each of these parameters plays a critical role in determining the biosensor's suitability for real-world agricultural environments, where biological complexity, environmental variability, and the need for real-time decision-making converge.

1) **Selectivity** is perhaps the most crucial attribute in fruit quality monitoring, as it defines the biosensor's ability to detect a specific analyte in the presence of numerous potentially interfering substances. Fruits are biochemically rich matrices containing sugars, acids, pigments, and volatile compounds. A highly selective biosensor ensures that, for example, glucose is accurately detected without interference from fructose or sucrose—essential for assessing ripeness in mangoes or bananas. Similarly, ethylene sensors must distinguish this ripening hormone from other VOCs released during respiration or microbial activity. High selectivity underpins the reliability of biosensor data, enabling precise grading, sorting, and harvest timing.

2) **Sensitivity** refers to the biosensor's capacity to detect minute concentrations of an analyte, often at nanomolar or even picomolar levels. This is particularly important in early-stage detection of spoilage, nutrient degradation, or contamination. For instance, amperometric biosensors used to monitor ascorbic acid (Vitamin C) in citrus fruits must detect subtle declines that signal loss of nutritional value. Likewise, electrochemical sensors designed to detect pesticide residues—such as organophosphates on apple skin—must operate at extremely low detection limits to ensure food safety. High sensitivity allows for proactive interventions, reducing post-harvest losses and enhancing consumer protection.

3) **Linearity** ensures that the biosensor's output signal maintains a direct, proportional relationship with the analyte concentration across a defined range. This characteristic is vital for quantitative analysis, particularly in automated systems used for fruit sorting and grading. For example, pH sensors used to monitor acidity in grapes must provide a linear response to varying concentrations of citric and malic acids throughout the ripening process. A linear response curve enables accurate calibration, simplifies data interpretation, and supports integration with digital platforms for real-time quality control.

4) **Response Time** is a critical operational parameter, especially in dynamic agricultural settings. It defines how quickly a biosensor can generate a stable and measurable signal after exposure to the analyte, typically measured as the time to reach 95% of the final signal. In fruit quality assessment, rapid response is essential for on-the-spot decisions during harvest, transport, or storage. For example, a biosensor used to evaluate firmness or sugar content in mangoes must deliver results within seconds to be practical in field conditions. Fast response times enhance workflow efficiency and reduce the risk of spoilage due to delays in handling.

5) **Reproducibility** reflects the biosensor's ability to deliver consistent results across repeated measurements of the same sample. This is particularly important in quality assurance protocols where uniformity across batches and locations is essential. A biosensor used to assess the ripeness of apples, for instance, must yield consistent glucose readings regardless of operator, device, or environmental conditions. High reproducibility builds confidence in biosensor data, facilitates regulatory compliance, and supports standardization in fruit grading systems.

6) **Stability** refers to the biosensor's ability to maintain its performance over time, resisting degradation due to environmental stressors such as temperature fluctuations, humidity, and exposure to organic compounds. In agricultural applications, biosensors may be deployed in open fields, cold storage units, or transport containers. A stable biosensor ensures long-term reliability without frequent recalibration or replacement. For example, a banana peel-based biosensor designed to detect phenolic compounds in fruit juices must retain enzymatic activity over several days to be viable for commercial use. Stability also influences the shelf life and cost-effectiveness of biosensor-based systems (Theavenot et al., 2001).

III. CLASSIFICATION AND PRINCIPLES OF MAJOR BIOSENSOR TYPES

3.1 Electrochemical Biosensors:

Definition: Electrochemical biosensors are highly sensitive analytical devices designed to detect specific biological or chemical compounds by converting biochemical events into electrical signals that can be measured and quantified. These biosensors consist of two primary components: (1) a biorecognition element—enzyme, antibody, nucleic acid (DNA/RNA), or aptamer—that selectively interacts with the fruit analyte and (2) an electrochemical transducer that converts this biochemical interaction into electrical output.

Types: Electrochemical biosensors used in fruit quality sensing can be classified based on the type of electrical signal they generate:

- **Amperometric biosensors** measure current produced from oxidation or reduction reactions.
- **Potentiometric biosensors** measure changes in electric potential (voltage).
- **Conductometric biosensors** measure changes in electrical resistance or conductivity.
- **Voltammetric biosensors** record current as the voltage is swept across a range.

Working Principle: The operating mechanism begins with a specific molecular interaction between the biorecognition element and the analyte present in the fruit. When the analyte binds to the recognition element on the electrode surface, a biochemical reaction—often involving oxidation or reduction—occurs, resulting in electron transfer. These electrons are captured by the electrochemical transducer, producing a measurable electrical signal whose magnitude correlates directly with analyte concentration (Naresh and Lee, 2021).

Applications in Fruit Quality: Amperometric glucose biosensors track sugar accumulation during ripening in apples, mangoes and bananas. Potentiometric pH biosensors evaluate acidity changes in grapes and citrus fruits. Voltammetric sensors quantify antioxidant compounds like polyphenols and vitamin C. Conductometric biosensors detect spoilage-related metabolites such as ethanol and CO_2. Gas-phase electrochemical sensors detect ethylene release for shelf-life prediction (Liu et al., 2025).

3.2 Optical Biosensors:

Definition: Optical biosensors are analytical devices that detect biological interactions by monitoring changes in light-based properties such as fluorescence, absorbance, chemiluminescence or refractive index resulting from the interaction between a target analyte and a biorecognition element.

Types:

- **Fluorescence biosensors** detect changes in natural or induced fluorescence.
- **Chemiluminescence biosensors** measure light emission generated during biochemical reactions.
- **Surface Plasmon Resonance (SPR) biosensors** measure shifts in refractive index.
- **Optical fiber sensors** transmit optical signals through fiber cables.

Working Principle: When an analyte binds to the sensing surface, the resulting biochemical interaction alters optical characteristics (fluorescence emission, light absorption, refractive index, or light scattering). The transducer converts these optical variations into electrical signals that correlate directly with the analyte concentration (Estevez et al., 2022).

Applications: Fluorescence-based sensors detect chlorophyll degradation to determine maturity in mangoes and tomatoes. Chemiluminescence sensors quantify antioxidants in citrus and berries. SPR-based sensors detect ethylene gas emission to predict ripening stages. Optical fiber sensors monitor volatile organic compounds (VOCs) to identify early spoilage during storage (Burcu et al., 2023).

3.3 Electronic Biosensors (FET-based):

Definition: Electronic biosensors, particularly those built on Field-Effect Transistor (FET) platforms, are advanced analytical devices that monitor biological or chemical analytes by measuring changes in electrical conductivity across a semiconductor channel.

Types:

- **Ion-Sensitive Field Effect Transistors (ISFETs)** detect ions such as hydrogen ions (H^+).
- **Metal-Oxide Semiconductor FETs (MOSFETs)** incorporate metal-oxide nanomaterials.
- **Organic FETs (OFETs)** utilize conductive polymers.
- **Nanowire or graphene-FET biosensors** enable detection of VOCs and ethylene gas.

Working Principle: When analytes such as glucose or ethylene interact with immobilized enzymes or aptamers, charge accumulation or depletion occurs at the gate-electrolyte interface. This alters the electric field and changes the conductivity of the semiconductor channel between the source and drain (Mishra, Srivastava and Ramnani, 2022).

Applications: ISFET sensors measure pH in grape and citrus juice. MOSFET and nanomaterial-enhanced FETs detect glucose and phenolic compounds. Graphene-FET sensors detect trace levels of ethylene and VOCs for spoilage prediction (Zhang et al., 2024).

3.4 Colorimetric Biosensors:

Definition: Colorimetric biosensors are analytical devices that detect specific biological or chemical substances by producing a visible colour change as a result of biochemical interactions between the target analyte and an immobilized biorecognition element.

Types:

- **Enzymatic colorimetric biosensors** utilize enzymes such as glucose oxidase.
- **Nanoparticle-based biosensors** use gold (AuNPs) or silver nanoparticles (AgNPs).
- **pH-sensitive colorimetric biosensors** use dyes or natural pigments.

Working Principle: The fruit analyte interacts with a biorecognition layer, initiating a catalytic or binding event that causes a colour change. For enzymatic sensors, enzymes oxidize the analyte, generating H_2O_2 which reacts with a chromogenic substrate. In nanoparticle-based sensors, target molecules induce aggregation or dispersion of nanoparticles, creating visible optical shifts (Zhang et al., 2024).

Applications: GOx-based colorimetric strips monitor ripening in mangoes, bananas, and apples. PPO-based sensors detect phenolic compounds in grapes and berries. Nanoparticle-based sensors detect spoilage gases in smart packaging. pH sensors provide real-time visual alerts of fruit spoilage (Soni and Pandey, 2021).

3.5 Acoustic and Piezoelectric Biosensors:

Definition: Acoustic biosensors assess fruit quality by detecting changes in acoustic wave properties such as frequency, amplitude, or phase in response to biochemical or physical interactions on the sensor surface.

Types:

- **Bulk Acoustic Wave (BAW) biosensors** transmit waves through the entire substrate.
- **Surface Acoustic Wave (SAW) biosensors** propagate waves along the surface.
- **Quartz Crystal Microbalance (QCM)** detects mass changes on quartz crystal surface.

Working Principle: When fruit-derived molecules interact with the biorecognition surface, mass and viscoelastic properties change, altering frequency, velocity, and amplitude of acoustic waves. The magnitude of shift is proportional to the amount of analyte (Singh et al., 2023).

Applications: Detect firmness, internal texture, ripeness stage, and mechanical or microbial damage. SAW-based devices detect ethylene and VOC emissions for ripening prediction. Used in automated sorting and grading systems (Kaur and Kundu, 2024).

IV. ASSOCIATED SENSING TECHNOLOGIES FOR HOLISTIC QUALITY ASSESSMENT

4.1 Optical & Spectroscopic Techniques:

4.1.1 Near-Infrared Spectroscopy (NIRS):

Definition: Non-destructive technique measuring interaction of near-infrared light (780–2500 nm) with fruit tissues to determine internal biochemical composition.

Working Principle: NIR light interacts with fruit tissue; molecular bonds absorb energy at characteristic wavelengths. Detector captures reflected light spectrum representing biochemical properties.

Applications: Determine soluble solid content (SSC), titratable acidity (TA), ripeness, internal defects. Portable devices enable real-time quality grading (Cozzolino, 2016).

4.1.2 Hyperspectral Imaging (HSI):

Definition: Integrates imaging with spectroscopy to capture both spatial and spectral information (400-2500 nm).

Working Principle: Captures hundreds of narrow wavelength bands forming a hypercube. Machine learning algorithms extract features to predict quality parameters.

Applications: Quantify vitamin C, sugar content, organic acids. Detect early decay, mechanical damage, pest infestation (Xiang et al., 2022).

4.1.3 Visible Light Imaging:

Definition: Image-based sensing using visible spectrum (400–700 nm) cameras.

Working Principle: Captures surface attributes (shape, size, colour, texture). Computer vision and deep learning analyze images for quality assessment.

Applications: Classify fruit maturity, detect defects and diseases, automated sorting and grading (Cheng, Yu and Ying, 2021).

4.2 Electromagnetic & Imaging Techniques:

4.2.1 Nuclear Magnetic Resonance (NMR):

Definition: Measures magnetic behaviour of atomic nuclei in external magnetic field.

Working Principle: Nuclei emit resonance signals converted to spectra providing composition and structural information.

Applications: Quantify metabolites (sugars, acids, antioxidants), detect bruises, rot, tissue degradation (Wang et al., 2018).

4.2.2 Terahertz Imaging:

Definition: Uses electromagnetic waves (0.1–10 THz) between microwave and infrared regions.

Working Principle: THz waves interact with water, sugars, organic compounds; absorption/transmission changes reveal quality parameters.

Applications: Monitor moisture, sugar levels, pesticide residues, internal bruising (Chen et al., 2018).

4.3 Acoustic & Vibroacoustic Techniques:

4.3.1 Ultrasonic Sensors:

Definition: Uses high-frequency acoustic waves (20 kHz to 500 MHz) to evaluate internal quality.

Working Principle: Wave propagation affected by firmness, moisture, cellular structure. Velocity and attenuation changes indicate quality.

Applications: Assess firmness, maturity, detect internal defects and pest infestation (Mizrach et al., 2008).

4.3.2 Vibration Analysis:

Definition: Analyzes acoustic/vibrational responses to mechanical excitation.

Working Principle: Measures frequency, amplitude, attenuation correlated with firmness, elasticity, internal structure. **Applications:** Evaluate hardness, texture, ripeness, classify maturity stages (Chen et al., 2018).

4.4 Gas & Volatile Sensing:

4.4.1 Electronic Nose (E-nose):

Definition: Biomimetic olfactory system detecting volatile organic compounds (VOCs).

Working Principle: Sensor array interacts with VOCs, generating electrical signals analyzed by pattern recognition algorithms.

Applications: Ripeness monitoring, aroma profiling, spoilage detection, disease identification (Guo et al., 2022).

4.5 Electrical Property Sensing:

4.5.1 Dielectric Property Sensors:

Definition: Evaluates interaction of fruit tissues with electromagnetic fields.

Working Principle: Measures complex dielectric constant (storage and loss) sensitive to moisture, sugars, tissue structure.

Applications: Monitor ripening, postharvest deterioration, disease detection, physical damage assessment (Nelson & Trabelsi, 2022).

V. INTEGRATED APPLICATIONS IN FRUIT QUALITY MONITORING

TABLE 1
BIOSENSOR APPLICATIONS IN FRUIT QUALITY MONITORING

Application	What It Measures	Sensor Types	Example Use
Ripeness/Maturity	Sugars, acids, pigments, VOCs, firmness	Electrochemical, Optical, E-nose, Acoustic	Harvest timing, sorting ripe/unripe fruits
Sweetness (SSC)	Sugar concentration (°Brix)	Enzyme-based, Dielectric, NIR	Grading grapes, apples, mangoes
Acidity & Taste Balance	Sugar-acid ratio, pH	pH sensors, Ion-selective, Electrochemical	Citrus harvest, flavour grading
Firmness/Texture	Internal structure, bruising	Acoustic, Piezoelectric	Sorting apples, detecting melon damage
Aroma/VOCs	Volatile compounds	E-nose, GC-MS	Ripening stage, spoilage detection
Browning/Oxidation	Phenolic oxidation	Enzyme-based, Optical, Electrochemical	Shelf-life prediction for cut fruits
Ethylene/Gas Monitoring	Ripening gases	Gas sensors, E-nose, Optical	Storage control, transit monitoring
Moisture Content	Water status	Dielectric, Impedance, NIR	Drying control, freshness check
Nutritional Compounds	Vitamins, antioxidants	Electrochemical, Optical, Aptamer-based	Health labelling, antioxidant sorting
Residue Detection	Pesticides, chemicals	Immunosensors, Electrochemical	Compliance checks, farm safety

VI. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant advances, several challenges impede widespread commercialization of biosensors in horticulture:

- **Stability and Reliability:** Biosensor performance degrades under field conditions due to temperature fluctuations, humidity, and organic interference.
- **Standardization:** Lack of uniform protocols for calibration, validation, and data interpretation across different platforms.
- **Cost and Scalability:** High production costs of nanomaterial-enhanced and FET-based biosensors limit large-scale deployment.
- **Multiplexing:** Most biosensors detect single analytes; simultaneous multi-analyte detection remains technically challenging.
- **Integration with Farming Practices:** Adapting laboratory prototypes to user-friendly, rugged devices suitable for farmers and supply chain workers.

Future developments should focus on:

- **Nanomaterial Innovation:** Using graphene, CNTs, and metal-organic frameworks to enhance sensitivity, stability, and selectivity.

- **IoT and AI Integration:** Wireless biosensor networks transmitting real-time data to cloud platforms for predictive analytics and automated decision-making.
- **Flexible and Wearable Sensors:** Developing biodegradable, flexible biosensors for direct fruit attachment or smart packaging.
- **Multiplexed Systems:** Lab-on-a-chip devices capable of detecting multiple quality parameters simultaneously.
- **Global Standards:** Establishing international standards for biosensor validation, data sharing, and quality assurance in horticulture.

VII. CONCLUSION

Biosensors have emerged as transformative tools in fruit quality assessment, offering rapid, non-destructive, and highly specific analysis across the entire horticultural supply chain. By integrating biological recognition elements with advanced transduction mechanisms—electrochemical, optical, electronic, colorimetric, acoustic and potentiometric—these devices enable precise monitoring of key quality indicators such as sugar content, acidity, firmness, aroma, and spoilage markers. Their ability to detect trace analytes like glucose, ethylene and VOCs in real time supports informed decision-making during harvest, postharvest handling, storage and retail.

The evolution from first-generation enzyme electrodes to third-generation nano-enabled FET biosensors reflects a trajectory of increasing sensitivity, miniaturization and integration with smart technologies. Coupled with IoT and AI platforms, biosensors now facilitate automated grading, predictive analytics and traceability, aligning with the goals of precision horticulture and sustainable agriculture.

As biosensor technologies continue to advance, their role in enhancing fruit quality, reducing postharvest losses and ensuring consumer satisfaction will become increasingly central. Future innovations will likely focus on multi-analyte detection, wearable formats and smart packaging systems, further embedding biosensors into the digital transformation of horticultural science. To realize their full potential, collaborative efforts among researchers, engineers, growers, and policymakers are essential to address existing challenges and accelerate the adoption of these eco-friendly smart applications in green horticulture.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Valorization of *Lemna minor* Leaves via Solid-State Fermentation by a Fish-Gut *Bacillus subtilis* for Aquafeed Application

Dr. Argha Khan

Department of Zoology. Vivekananda Mahavidyalaya. Burdwan - 713103

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***Abstract*—** *This study aimed to enhance the nutritional value of the freshwater macrophyte Lemna minor (duckweed) for use as an aquafeed ingredient through Solid-State Fermentation (SSF). A phytase-producing bacterium, Bacillus subtilis (HM352551), isolated from the gut of the teleost fish Labeo bata, was used as the fermenting agent. Key SSF parameters were optimized for maximum phytase yield. The highest phytase activity of 15.26 ± 0.09 U/g was achieved after a 10-day incubation at 35°C, with an initial substrate moisture content of 50% and a moistening media pH of 7.0. An inoculum size of 4% (v/w) also yielded high activity (14.28 ± 0.11 U/g). Proximate composition analysis of the fermented leaf meal revealed a significant increase ($p < 0.05$) in crude protein, lipid, ash, and mineral content (Na, K, Ca, Mg, P, Zn, Fe, Cu, Mn). The levels of all essential amino acids increased. Concurrently, there was a significant reduction ($p < 0.05$) in antinutritional factors, including crude fibre, phytic acid, trypsin inhibitor, and tannin. Concentrations of heavy metals (Pb, Cd, Cr, Ni) were also reduced. The results demonstrate that SSF using a host-derived gut bacterium is an effective strategy for the bioconversion of low-cost aquatic weeds into a nutritionally enhanced, safer, and sustainable component for aquafeed formulations.*

Keywords*— *Bacillus subtilis, phytase, Lemna minor, solid-state fermentation, aquafeed, antinutritional factors.

I. INTRODUCTION

In recent years, diverse terrestrial and aquatic macrophytes have been incorporated into carp diets as partial replacements for costly fishmeal [1]. As protein is a critical component for fish growth, alternative plant protein sources have been explored from the early days of freshwater aquaculture [2]. Duckweed, *Lemna minor*, is considered a promising natural feed for carps [3,4] due to its relatively high protein content, favourable amino acid profile, and small size [5]. Its leaves contain low fibre, and the cell walls have low lignin content [6]. Duckweed is also a source of trace minerals like potassium and phosphorus, as well as pigments such as carotenes and xanthophylls [7].

However, plant-based ingredients contain antinutritional factors (ANFs) like tannins, phytic acid, trypsin inhibitors, and saponins, which reduce nutrient digestibility and bioavailability [8]. Solid-State Fermentation (SSF) using exo-enzyme-producing microorganisms is an effective method to reduce ANFs [8]. SSF is often preferred over submerged fermentation due to its higher product concentration, lower energy and wastewater output, simpler operation, and reduced space requirements [9].

Indigenous phytase-producing bacteria from fish guts are advantageous for fermenting plant materials. Their enzymes can offer precise activity, protease resistance, and high catalytic efficiency compared to fungal alternatives [9]. Using invasive aquatic weeds as an SSF substrate provides economic benefits via low-cost biomass and enables sustainable nutrient recovery.

The primary objective of this research was to ferment *Lemna minor* leaves using an autochthonous fish-gut bacterium, *Bacillus subtilis* (HM352551), to degrade ANFs and improve nutrient bioavailability, thereby evaluating its potential as a beneficial ingredient in aquaculture feeds.

II. MATERIALS AND METHODS

2.1 Microorganism and Inoculum Preparation:

The phytase-producing bacterium used was isolated from the gut of *Labeo bata* and identified as *Bacillus subtilis* (GenBank Accession No. HM352551) via 16S rRNA gene sequencing [10]. The culture was maintained on modified phytase screening medium (MPSM) agar [11]. Inoculum was prepared by growing the culture in MPSM broth at 35°C for 48 hours, yielding a suspension containing approximately 5.6×10^7 cells mL^{-1}.

2.2 Substrate Collection and Processing:

Lemna minor leaves were collected from local water bodies in Burdwan, West Bengal, India (23°12' N, 87°45' E). The fresh leaves were oven-dried at 70°C for 48 hours, ground into a fine powder using a laboratory blender, and stored as *Lemna* Leaf Meal (LLM) for use as the solid fermentation substrate.

2.3 Solid-State Fermentation (SSF):

Five grams of dry LLM was placed in a 250 mL Erlenmeyer flask. The substrate was moistened with 3 mL of MPSM broth (lacking sodium phytate and agar) and additional distilled water to achieve the desired final moisture level. The flask was plugged with cotton and sterilized at 121°C and 15 psi for 20 minutes. After cooling, the substrate was aseptically inoculated with 1 mL of bacterial suspension. Fermentation was carried out at 35°C for 72 hours. All experiments were performed in triplicate.

2.4 Optimization of SSF Parameters:

SSF was conducted to maximize phytase production and phytate hydrolysis. The following parameters were optimized: incubation temperature (25–50°C), initial pH of the moistening medium (pH 5–9), fermentation period (24–144 hours), inoculum size (1–5 mL), and initial substrate moisture content (10–100%).

2.5 Enzyme Extraction and Phytase Assay:

After fermentation, phytase was extracted from the solid substrate [8]. Phytase activity was assayed using sodium phytate as the substrate [12]. One unit (U) of phytase activity was defined as the amount of enzyme required to release 1 µg of inorganic phosphorus per minute under assay conditions. Activity was expressed as units per gram of dry substrate (U/g). The soluble protein in the crude extract was estimated by the Lowry method [13] using bovine serum albumin as the standard.

2.6 Proximate, Mineral, and Antinutrient Analysis:

Proximate composition (crude protein, lipid, fibre, ash) of raw and fermented LLM was analyzed using standard AOAC methods [14]. Mineral elements (Na, K, Ca, Mg, P, Zn, Fe, Cu, Mn) were analyzed by atomic absorption spectrophotometry (PerkinElmer Analyst 700) and flame photometry. Tannin [8], phytate [15], and trypsin inhibitor activity [16] were determined. Amino acid profiles were analyzed using an automated amino acid analyzer (Shimadzu-10AS). Fatty acids were quantified by GC-MS (Shimadzu GC-MS-QP2010).

2.7 Statistical Analysis:

All data are presented as mean ± standard error (SE) of three replicates. A t-test was used to compare means between raw and fermented LLM. One-way ANOVA followed by the Student-Newman-Keuls test was applied to analyze the effect of different SSF parameters on phytase yield. Analyses were performed using SPSS Version 16.0, with significance accepted at $p < 0.05$.

III. RESULTS

3.1 Optimization of SSF Conditions for Phytase Production:

Phytase production was significantly influenced by all tested parameters ($p < 0.001$, ANOVA). Activity increased with incubation time, reaching a maximum of 12.39 ± 0.09 U/g on day 10, followed by a decline (Fig. 1d). The optimum initial pH of the moistening medium was 7.0, yielding 12.41 ± 0.10 U/g (Fig. 1b). A sharp decline occurred at higher or lower pH. The optimum incubation temperature was 35°C, resulting in the highest activity of 15.21 ± 0.09 U/g (Fig. 1c). The initial substrate moisture content of 50% was optimal, producing 15.26 ± 0.09 U/g (Fig. 1a). An inoculum size of 4 mL (equivalent to 4% v/w) gave maximum activity (14.28 ± 0.11 U/g), with a decline at higher inoculum levels (Fig. 1e).

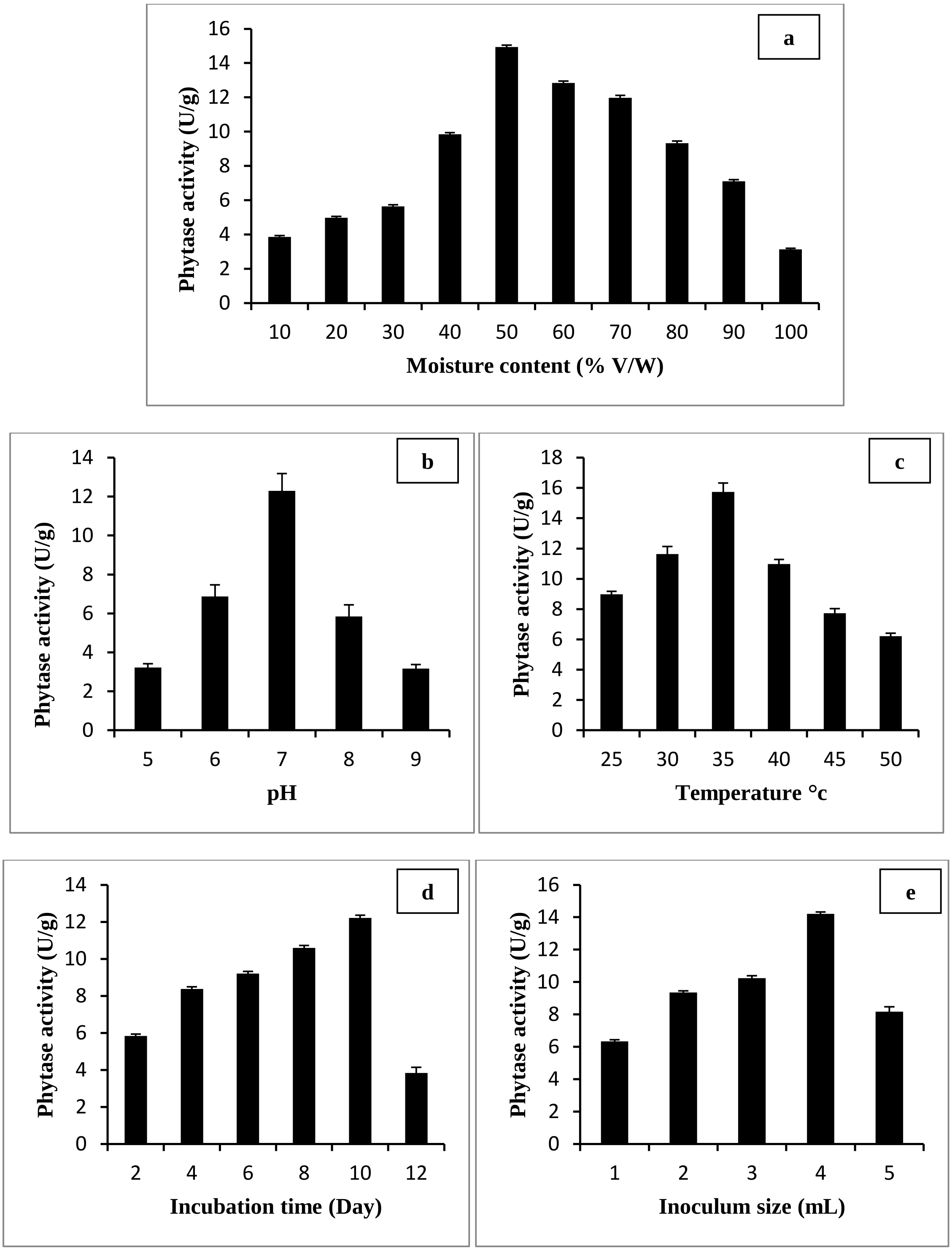

FIGURE 1: Effect of different initial moisture content (a), initial pH of moistening media (b), temperature (c), incubation period (d), and inoculum size (e) on phytase production in solid-state fermentation (SSF). Bars with different alpha plates are statistically significant ($p < 0.001$; Student-Newman-Keuls test)

3.2 Effect of Fermentation on Substrate Composition:

Fermentation under optimal conditions significantly altered the composition of LLM (Table 1). Crude protein increased by 9.74%, lipid by 15.30%, and ash by 23.05%. Crude fibre content decreased substantially by 39.87%. All analyzed macro- and micro-elements showed significant increases ($p < 0.05$). Concentrations of the antinutritional factors phytic acid, tannin, and trypsin inhibitor activity were reduced by 70.91%, 67.68%, and 57.50%, respectively. The levels of all essential and non-essential amino acids increased significantly. The content of individual saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fatty acids also increased. Furthermore, the concentrations of heavy metals (Pb, Cd, Cr, Ni) were reduced.

TABLE 1
PROXIMATE COMPOSITION AND CONCENTRATION OF DIFFERENT MINERAL IONS , ANTINUTRITIONAL FACTORS AMINO ACIDS AND FATTY ACIDS IN RAW AND FERMENTED *LEMNA MINOR* LEAF MEAL (LLM)

Parameters	Raw	SSF processed	% Increase / Reduction (↓)
Nutrients			
Crude Protein	17.87 ± 0.08	19.61 ± 0.11	9.74
Crude Lipid	1.83 ± 0.03	2.11± 0.05	15.30
Crude Fibre	11.16 ± 0.05	6.71 ± 0.04	39.87 ↓
Crude Ash	3.21 ± 0.05	3.95 ± 0.05	23.05
Macro elements (g/kg)			
Ca	14.74 ± 0.11	15.82 ± 0.12	7.32
K	8.7 ± 0.18	9.4 ± 0.21	8.33
P	6.5 ± 0.09	7.41± 0.11	13.85
Na	2.24 ± 0.06	2.50 ± 0.05	11.75
Mg	5.1 ± 0.03	5.34 ± 0.03	4.65
Microelements (mg/kg)			
Fe	46 ± 0.09	53 ± 0.09	15.22
Zn	18 ± 0.17	19.05 ± 0.11	5.82
Mn	17 ± 1.05	18.40 ± 1.03	8.23
Cu	2.2 ± 0.04	2.46 ± 0.04	12.03
B	12.24±0.08	13.12±0.09	7.23
Mo	0.3±0.02	0.4±0.02	33.33
Heavy Metals (mg/kg)			
Pb	2.29 ±0 .05	1.96 ± 0.07	8.30↓
Cd	0.79 ± 0.04	0.67 ± 0.03	15.19↓
Cr	5.73±0.06	4.81±0.02	16.06↓
Ni	3.11±0.03	2.48±0.03	20.26↓
Antinutritional factors (g %)			
Phytate	1.26 ± 0.03	0.64 ± 0.03	70.91 ↓
Tannin	0.99± 0.03	0.32 ± 0.02	67.68 ↓
Trypsin inhibitor	1.20 ± 0.04	0.51 ± 0.03	57.50 ↓
Amino acid Composition (g/100g protein)			
Alanine	7.4 ± 0.03	7.8 ± 0.04	5.41
Arginine	3.9 ± 0.04	4.2 ± 0.03	7.70
Cysteine	1.2 ± 0.05	1.4 ± 0.05	16.67
Glutamic acid	12.2 ± 0.05	12.5 ± 0.05	2.46
Methionine	1.7 ± 0.04	1.9 ± 0.03	11.76
Leucine	8.6 ± 0.05	8.9 ± 0.05	3.49
Valine	6.4 ± 0.03	6.7 ± 0.04	4.69
Lysine	5.8 ± 0.04	6.1 ± 0.05	5.17
Phenyl alanine	6.3 ± 0.05	6.6 ± 0.04	4.76
Glycine	4.4 ± 0.05	4.7 ± 0.03	6.81
Aspertic acid	11.1± 0.04	11.4 ± 0.06	2.70

Parameters	**Raw**	**SSF processed**	**% Increase ()/ Reduction (↓)**
Histidine	2.4±0.03	2.6±0.04	8.33
Serine	5.2±0.05	5.6±0.05	7.69
Proline	4.5±0.04	4.7±0.05	4.44
Tryotophan	1.35±0.02	1.38±0.03	2.22
Fatty cids (g FAME/100 g crude fat)			
SFA – saturated fatty acids			
C8:0	0.134±0.05	0.142±0.03	5.97
C10:0	0.263±0.02	0.284±0.02	7.98
C12:0	0.210±0.02	0.223±0.02	6.19
C14:0	1.312±0.05	1.411±0.04	7.55
C15:0	0.081±0.03	0.092±0.03	13.58
C16:0	11.96±0.09	12.35±0.06	3.26
C17:0	0.031±0.01	0.036±0.01	16.13
C18:0	4.625±0.04	4.930±0.02	6.59
C20:0	0.046±0.01	0.053±0.01	15.22
C24:0	0.061±0.02	0.068±0.03	11.48
MUFA – monounsaturated fatty acids			
C14:1 c7	0.082±0.01	0.087±0.01	6.58
C15:1 c10	0.081±0.02	0.087±0.01	7.24
C16:1 c7	0.173±0.02	0.184±0.02	6.81
C16:1 c9	0.168±0.01	0.178±0.01	5.99
C16:1 c10	0.554±0.01	0.589±0.02	6.32
C18:1 c11	0.176±0.02	0.191±0.03	8.26
C18:1 c9	5.763±0.05	6.115±0.05	6.11
PUFA – polyunsaturated fatty acids			
C16:2 c9,c12	1.213±0.06	1.313±0.06	8.24
C18:2 c9,c12	11.386±0.08	12.226±0.06	7.37
C18:3 c9,c12,c15	15.269±0.08	16.217±0.05	6.21
C20:2 c11,c14	0.021±0.01	0.022±0.02	5.48

IV. DISCUSSION

The results demonstrate that SSF using *Bacillus subtilis* from fish gut effectively enhanced the nutritional profile of *L. minor*. The optimal pH (7.0) and temperature (35°C) for phytase production align with the neutral/alkaline gut environment of the host fish (*L. bata*) and the mesophilic nature of the bacterium [11]. The decline in activity beyond optimal moisture (50%) and inoculum size (4%) is consistent with reports suggesting impeded aeration and nutrient competition at higher levels [22, 24].

The significant reduction in phytic acid, tannin, and trypsin inhibitor is attributable to the extracellular phytase and other enzymes (e.g., protease, cellulase) produced by *B. subtilis* [11]. The degradation of the fibrous matrix likely contributed to the decrease in crude fibre and the concomitant increase in the relative concentration of protein, lipids, and minerals. The increase in amino acid levels may result from microbial synthesis or the liberation of bound protein fractions. The reduction in heavy metals, though from low baselines, suggests a potential biosorption or biotransformation capability of the bacterial biomass, warranting further investigation.

The use of a host-derived probiotic bacterium for feed processing ensures metabolic compatibility and safety for the target aquatic species. The substantial reduction in ANFs, coupled with improved nutrient density, makes fermented LLM a promising alternative protein source for carp diets, potentially reducing reliance on fishmeal and the environmental impact of feed production [25, 29].

V. CONCLUSION

This study confirms that solid-state fermentation of *Lemna minor* leaf meal using a phytase-producing *Bacillus subtilis* strain isolated from fish gut is a viable bioprocessing strategy. The process significantly degraded antinutritional factors, improved the bioavailability of nutrients and minerals, and reduced heavy metal content. This approach valorizes a low-cost aquatic weed into a sustainable, nutrient-enhanced ingredient suitable for incorporation into aquafeeds, offering a pathway to reduce feed costs and environmental footprint in aquaculture.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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Marketable Surplus and Supply Chain Analysis of Wheat in the Mid Hills of Kangra Valley, Himachal Pradesh, India

Girish Mahajan[1*]; Kshitij Mandial[2]

[*1]Extension Specialist (Agricultural Economics), Krishi Vigyan Kendra-Bara –Hamirpur, Himachal Pradesh
[2]Ex- PG student, Department of Agricultural Economics, Extension Education, and Rural Sociology, CSKHPKV, Palampur
*Corresponding Author

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***Abstract*—** *An attempt has been made in this research to identify the major supply chains in the mid-hills of Kangra valley involved in the wheat business and the different functionaries transferring the produce from producer to consumer, along with their marketing costs, margin, price spread, efficiency, and the producer's share in the consumer's rupee. The supply chains were identified on the basis of form, place, time, and possession utility. Three marketing channels were found. Channel II (producer → primary wholesaler → secondary wholesaler → retailer → consumer) was the most preferred, with 56.86 per cent of the total wheat traded through it. Price spread was highest in Channel III (producer → local trader/commission agent → flour miller → retailer → consumer) due to the highest marketing margin (19.84%). The producer's share was highest in Channel I (97.73%) where cultivators sold directly to consumers, and lowest in Channel III (62.88%). Marketing efficiency was highest in Channel I (42.99%) as reduced intermediation lowered costs. The study concludes that a larger number of intermediaries increases marketing cost and margin, reduces the producer's share, and makes the channel less efficient.*

Keywords*— *Wheat, marketing channel, wholesaler, processor, retailer, consumer, price spread, producer's share, marketing efficiency.

I. INTRODUCTION

Wheat is the most important food crop in H.P. and is primarily cultivated during the *rabi* season across most of the state. The state has seen a reduction in the total area under wheat cultivation. In early 2024, the sowing area was reported to have dipped by 7,500 hectares in the northern zone, which includes Kangra, Una, Mandi, Hamirpur, and Chamba districts. In Kangra valley, a large portion of the agricultural land (around 80%) is rain-fed, making it highly vulnerable to rainfall deficits. A prolonged dry spell during December and January 2024 significantly impacted the crop, with the agriculture department estimating a potential 5-7% dip in wheat output.

The importance of a marketable surplus lies in providing farmers with income, while efficient supply chain management ensures this surplus reaches the market effectively, securing better prices and reducing losses. Together, they are crucial for farmer profitability and preventing distress sales, especially given challenges like lack of irrigation and market infrastructure. With this background, this research identifies the major supply chains and actors involved in transferring wheat from production to consumers in Kangra valley, along with an analysis of marketing cost, margin, price spread, efficiency, and the producer's share.

II. METHODOLOGY

2.1 Selection of the study area:

The study was purposely conducted in Kangra district of Himachal Pradesh, as it occupies the foremost position in wheat production within the state. As per the Statistical Abstract of Himachal Pradesh (2021–22), the district produced about 1,35,247 metric tonnes of wheat. The district also has an established network of agricultural markets and intermediaries, which enabled the mapping of multiple marketing channels.

2.2 Sampling Design and sample Selection:

Kangra district has fifteen development blocks. Multistage random sampling was followed. Firstly, two blocks, Indora and Nurpur, were randomly selected. In the second stage, five villages in each block were selected randomly. In the third stage, eight farmers were selected randomly from each selected village, making a total sample of 80 cultivators. The respondents were divided into Small (<1 ha) and Large (1-3 ha) holdings (Table 1).

TABLE 1
DISTRIBUTION OF SAMPLED HOUSEHOLDS ACCORDING TO THEIR SIZE OF LAND HOLDING

S.No.	Category of farmers	No. of Farmers
1	Small (<1 ha)	37
2	Large (1-3 ha)	43
3	Overall	80

2.3 Data collection:

Both primary and secondary data were collected. Primary data were collected by survey method using pre-tested schedules via personal interviews with cultivators, wholesalers, traders, flour millers, and retailers (five each). Secondary data were collected from government reports. Data were collected for the agricultural year 2024-25.

2.4 Analytical framework:

Cost concepts recommended by Commission for Agricultural Costs and Prices (CACP), Govt. of India, 2004 were employed. Supply chains were identified based on form, place, possession, and time utility. The following formulas were used:

- **Marketing cost:** TC = PC + ∑MCi
- **Marketing Margin:** Ami = PRi – (PPi + CMi)
- **Producer's price:** PF = PS – PC
- **Producer's share:** PS = (FP / RP) * 100
- **Marketing efficiency (Modified Acharya's method):** ME = (RP - MM) / (MC + MM)

III. RESULTS AND DISCUSSION

3.1 Production, Utilization, and Marketable Surplus:

The overall production of wheat was 38.12 q per farm (Table 2). Out of total production, 9.73% was used for self-consumption, 5.51% as seed retained, and 6.03% as payment in kind. The marketable surplus, which equaled the marketed surplus, was 30.01 q (78.73% of total produce). This high marketed surplus is consistent with Thakur (2024), who noted a similar proportion in Una district, underscoring wheat's role as a primary cash crop in the region.

TABLE 2
PRODUCTION AND UTILIZATION OF WHEAT

S.No.	Particulars	Overall per farm (q)	Percent
1	**Total Production**	**38.12**	**100**
2	**Utilization**		
i.	Self-consumption	3.71	9.73
ii.	Seed Retained	2.1	5.51
iii.	Payment in Kind	2.3	6.03
	Sub total (A)	**8.11**	**21.27**
3	**Marketable Surplus = Marketed Surplus (B)**	**30.01**	**78.73**

Note: B = Total Production - A. Source: Field survey data, 2024-25.

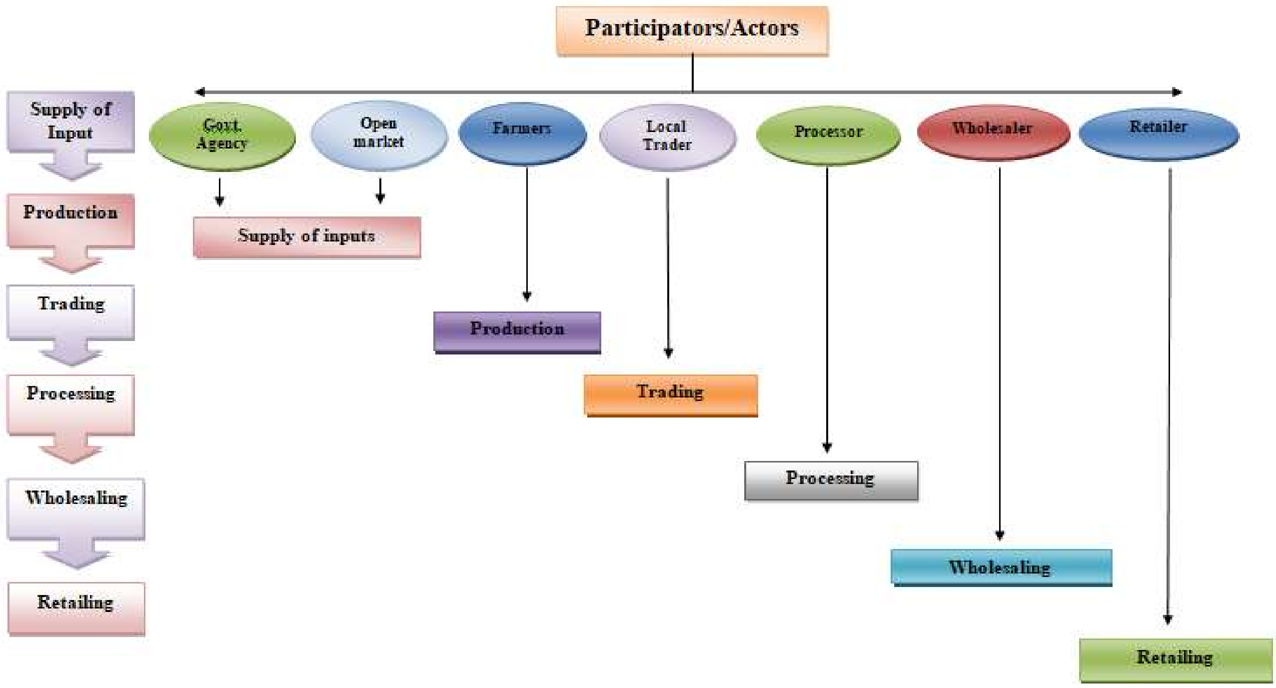

FIGURE 1: Flow chart of functions with participants to identify actors in wheat sector

3.2 Supply Chain Mapping and Input Procurement:

The supply chains were mapped based on form, place, time, and possession utility (Jassi, 2011). Input procurement data (Table 3) revealed that a majority of seeds (67.19%) were sourced from government agencies, while fertilizers (77.41%) and plant protection chemicals (81.06%) were primarily purchased from the open market. This preference for open markets for non-seed inputs aligns with Mandial (2025), who noted farmers prioritize easy availability and timely application.

TABLE 3
SOURCES OF INPUT PROCUREMENT IN THE STUDY AREA (%)

Particulars	Inputs	Small Farmers	Large Farmers	Overall
Sample Size (No. of Farmers)		**43**	**37**	**80**
Open Market	Seed	34.67	30.64	32.81
	Fertilizer	76.35	78.64	77.41
	Plant Protection Chemicals	79.47	82.9	81.06
Government Agency	Seed	65.33	69.36	67.19
	Fertilizer	23.65	21.36	22.59
	Plant Protection Chemicals	20.53	17.1	18.94
Own Source	Seed	25.58	20.47	23.22

Note: Percentages for each input type (Seed, Fertilizer, Plant Protection Chemicals) are calculated based on the number of farmers using that source. The "Own" category is for seeds only. Source: Field Survey.

3.3 Marketing Channels and Their Prevalence:

Three marketing channels were identified (Figure 2):

- **Channel I:** Producer → Consumer
- **Channel II:** Producer → Primary Wholesaler → Secondary Wholesaler → Retailer → Consumer
- **Channel III:** Producer → Local trader/Commission Agent → Flour Miller → Retailer → Consumer

Channel II was the most predominant, handling 56.86% of the marketed wheat, followed by Channel III (41.40%). Direct sales via Channel I were minimal (1.74%) (Table 4). This pattern, consistent with Thakur (2024) and Kumar (2022), highlights the near-total dependence of farmers on intermediary-based systems in the region.

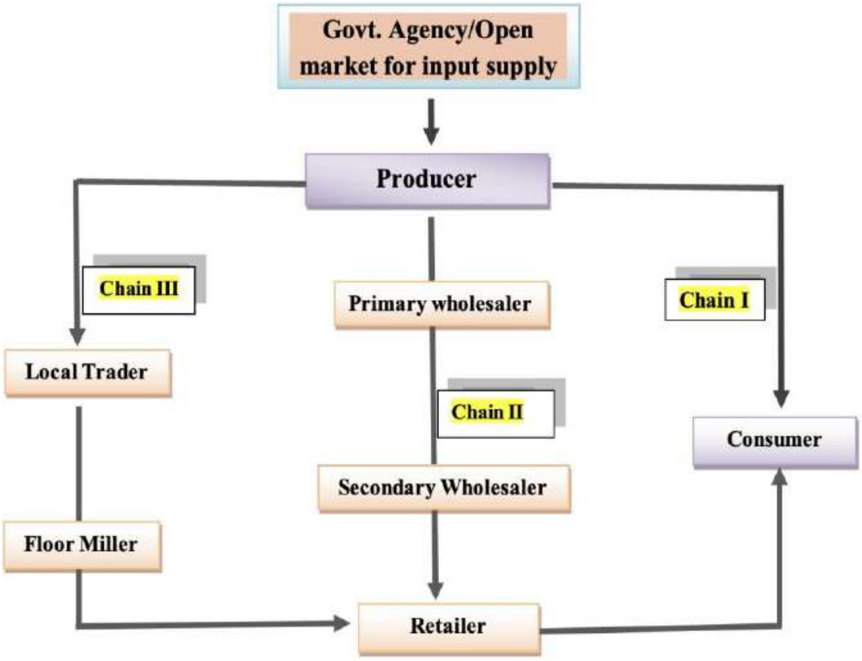

FIGURE 2: Different marketing channels of wheat in study area

TABLE 4
FARM CATEGORY-WISE QUANTITY OF WHEAT MARKETED THROUGH VARIOUS CHANNELS (%)

Marketing Channel	Market Intermediaries	Small Farmers	Large Farmers	Overall
Channel-I	Producer → Consumer	1.43	2.1	**1.74**
Channel-II	Producer → Primary Wholesaler → Secondary Wholesaler → Retailer → Consumer	54.51	59.6	**56.86**
Channel-III	Producer → Local Trader/Commission Agent → Flour Miller → Retailer → Consumer	44.06	38.3	**41.4**

Note: R = Retailer; C = Consumer. Source: Field Survey.

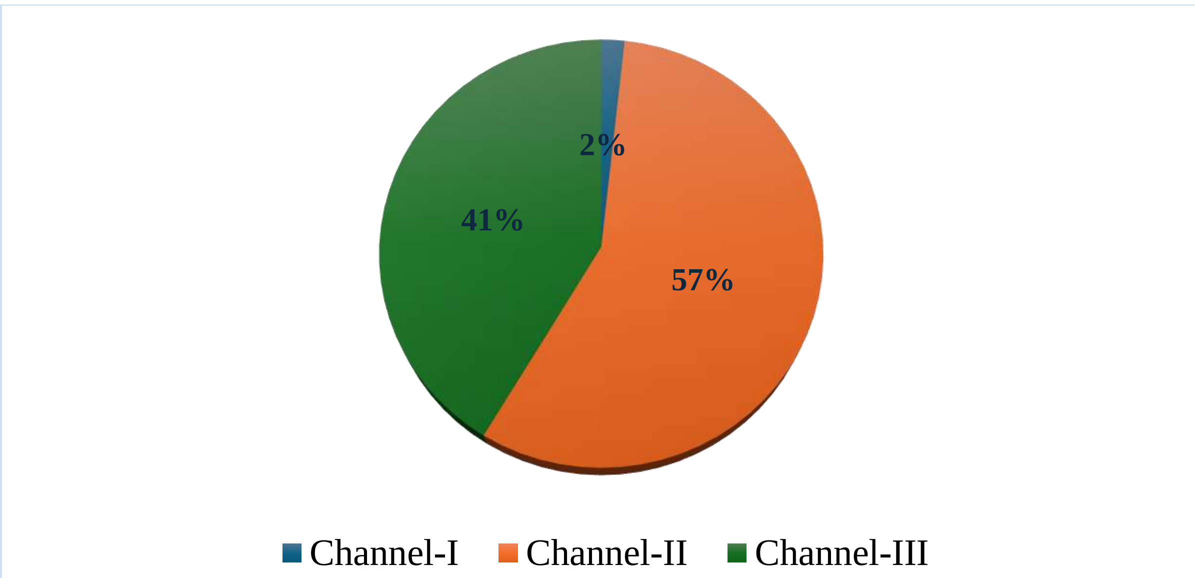

FIGURE 3: Farm category wise quantity of wheat marketed through various channels

3.4 Marketing Costs and Margins:

Marketing costs and margins for various intermediaries are presented in Table 5. The producer's net price varied between ₹2300.93 and ₹2490.65 per quintal across channels. In Channel III, the processor (flour miller) added substantial cost (₹150.00) and margin (₹494.27), leading to a significant price increase. In Channel II, costs and margins accumulated across primary wholesalers (₹98.52 cost, ₹56.02 margin) and secondary wholesalers (₹50.00 cost, ₹95.00 margin).

TABLE 5
MARKETING COSTS AND MARGIN OF DIFFERENT FUNCTIONARIES IN THE MARKETING CHANNELS OF WHEAT (₹/Quintal)

S.No.	Particulars	Channel-I	Channel-II	Channel-III
1	**Marketing cost incurred by producers**			
i.	Net price received by farmer	2490.65	2420	2300.93
ii.	Marketing cost incurred by producers	57.93	64.15	53.46
iii.	Farmer's selling price	2548.58	2484.15	2354.39
2	**Marketing cost incurred by Local trader/ Commission agent**			
i.	Gross price paid by Local Trader	–	–	2354.39
ii.	Marketing cost incurred by Trader	–	–	105.63
iii.	Trader Margin	–	–	61.85
iv.	Trader selling price	–	–	2521.87
3	**Marketing cost incurred by processor**			
i.	Gross price paid by processor	–	–	2521.87
ii.	Marketing cost incurred by Processor	–	–	150
iii.	Processor's selling price (Cost + Margin)	–	–	3400
of which:	Processor unit margin	–	–	494.27
4	**Marketing cost incurred by Primary Wholesaler**			
i.	Gross price paid by Wholesaler	–	2484.15	–
ii.	Marketing cost incurred by Wholesaler	–	98.52	–
iii.	Wholesaler's Margin	–	56.02	–
iv.	Wholesaler selling price	–	2638.69	–
	Marketing cost incurred by Secondary Wholesaler			
i.	Gross price paid by Wholesaler	–	2638.69	–
ii.	Marketing cost incurred by Wholesaler	–	50	–
iii.	Wholesaler's Margin	–	95	–
iv.	Wholesaler selling price	–	2783.69	–
5	**Marketing cost incurred by Retailer**			
i.	Gross price paid by Retailer	–	2783.69	3400
ii.	Marketing cost incurred by Retailer	–	90.58	89.36
iii.	Retailer Margin	–	120.38	170
iv.	Retailer Selling price / **Consumer's Purchase Price**	**2548.58**	**2994.65**	**3659.36**

Note: A dash (–) indicates that the particular functionary is not involved in the given channel. Source: Field Survey.

3.5 Price Spread, Producer's Share, and Marketing Efficiency:

A clear inverse relationship exists between channel length and efficiency (Table 6). **Channel I** was the most efficient (Index: 42.99) and provided the highest producer share (97.73%). **Channel II** showed moderate efficiency (4.21) and an 80.81%

producer share. **Channel III** was the least efficient (2.25) and delivered the lowest producer share (62.88%), with the highest price spread (37.12%) due to heavy marketing margins (19.84%).

TABLE 6
PRICE SPREAD AND MARKETING EFFICIENCY OF WHEAT AMONG DIFFERENT MARKETING CHANNELS

Particulars	Channel I	Channel II	Channel III
A. Price Components (₹/quintal)			
Producer's Net Price (PF)	2,490.65	2,420.00	2,300.93
Consumer's Price (RP)	2,548.58	2,994.65	3,659.36
Price Spread (RP - PF)	**57.93**	**574.65**	**1358.43**
Total Marketing Cost (MC)	57.93	303.25	398.45
Total Marketing Margin (MM)	0	271.4	726.12
B. Derived Metrics (%)			
Price Spread (%)	**2.27**	**19.19**	**37.12**
Marketing Cost (%)	2.27	10.13	10.89
Marketing Margin (%)	**0**	**9.06**	**19.84**
Producer's Share (%)	**97.73**	**80.81**	**62.88**
C. Efficiency Index			
Marketing Efficiency (ME)	**42.99**	**4.21**	**2.25**

Note: Calculated using modified Acharya's method: ME = (RP - MM) / (MC + MM).

This pattern confirms that each intermediary adds cost and takes a margin, widening the price spread and diminishing the farmer's share. The near absence of direct marketing suggests constraints like lack of market access, time, or volume, forcing farmers into less efficient chains (Dustagiri et al., 2013). The findings underscore the need for better market linkages, farmer cooperatives, and direct marketing strategies to enhance farmers' returns (Acharya and Pant, 2021).

IV. CONCLUSION

The study on the marketable surplus and supply chain of wheat in the mid-hills of Himachal Pradesh yields key conclusions. First, the marketable surplus was high at 78.73% of production. Second, three main marketing channels were identified. **Channel II (Producer → Primary Wholesaler → Secondary Wholesaler → Retailer → Consumer)** was the most predominant, handling 56.86% of the wheat. Third, the producer's share in the consumer's rupee was highest in Channel I (97.73%) and lowest in Channel III (62.88%). Fourth, marketing efficiency was highest in Channel I (42.99) and lowest in Channel III (2.25), with price spread directly correlating with the number of intermediaries.

All findings indicate that extended, multi-layered supply chains involving several functionaries reduce the farmer's share in the consumer's rupee. The presence of excessive middlemen increases marketing costs and lowers producer margins. To ensure fair prices and improve efficiency, it is essential to reduce unnecessary intermediaries. This can be achieved by promoting direct sales through local farmers' markets, strengthening Farmer Producer Organizations (FPOs) for collective bargaining and aggregation, and leveraging digital platforms to connect growers directly with consumers and bulk buyers.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Optimization of Plant Disease Detection and Classification Using an Antlion-Optimized VGG16 Model with Fuzzy Rough C-Means Segmentation

T. Kalaiselvi[1]; M. Natarajan[2]; P. Kaviya[3*]

[1]Assistant Professor, Department of Computer and Information Science, Annamalai University, Chidambaram, Tamil Nadu, India - 608 002.
[2]Assistant Professor, Department of Agricultural Extension, Annamalai University, Chidambaram, Tamil Nadu, India - 608 002.
[*3]Research Scholar, Department of Agricultural Extension, Annamalai University, Chidambaram, Tamil Nadu, India - 608 002.
*Corresponding Author

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Abstract— *The agricultural sector in India, supporting over 65% of the population, faces significant challenges from plant diseases that threaten crop productivity and food security. Traditional disease identification methods are often slow and require expert knowledge. This paper proposes a novel, automated framework for accurate plant disease detection by integrating advanced image processing with deep learning. The methodology employs a Median filter for image pre-processing, the Fuzzy Rough C-Means (FRCM) clustering algorithm for robust segmentation of diseased leaf regions, and a Convolutional Neural Network (CNN) for classification. The core innovation lies in enhancing a standard VGG16 CNN architecture using the Antlion Optimization (ALO) algorithm to optimize its hyperparameters, specifically the number of neurons in a fully connected layer, thereby improving feature learning and classification performance. Trained and tested on a dataset of cotton leaf images encompassing healthy samples and four disease types, the proposed ALO-enhanced VGG16 model achieved a high average classification accuracy of 93.33%. This performance surpasses that of other standard classifiers, including basic CNN, SVM, and ResNet models. The findings demonstrate that the integration of metaheuristic optimization with deep learning offers a powerful, scalable tool for precise plant disease diagnosis, with the potential to aid sustainable agricultural practices.*

Keywords— Plant Disease Detection, Image Segmentation, Fuzzy Rough C-Means (FRCM), Convolutional Neural Network (CNN), Antlion Optimization (ALO), VGG16.

I. INTRODUCTION

Agriculture is a vital global industry and a primary source of livelihood. Plant diseases, caused by pathogens such as fungi, bacteria, and viruses, represent a major threat to crop yield and quality, leading to significant economic losses [1, 2]. Early and accurate detection is crucial for implementing effective management strategies. Conventional visual inspection by experts is subjective, time-consuming, and not scalable. Consequently, there is a growing need for automated, reliable, and rapid diagnostic systems.

Computer vision and artificial intelligence offer promising solutions. Initial approaches utilized basic image processing for colour and texture analysis [6], while machine learning models like Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) were applied for classification [7, 8]. The advent of deep learning, particularly Convolutional Neural Networks (CNNs), has revolutionized the field due to their superior ability to automatically learn hierarchical and discriminative features from raw image data [9]. Models like VGG16 have become benchmarks in image classification tasks.

Despite their success, standard CNNs may not be optimally configured for specific domains like plant pathology. Their fixed architectures might be suboptimal for learning the distinctive features of various leaf diseases. This creates a research opportunity to customize and optimize these models. Furthermore, accurate segmentation of the diseased portion from the leaf background remains a challenge, especially under noisy or ambiguous conditions.

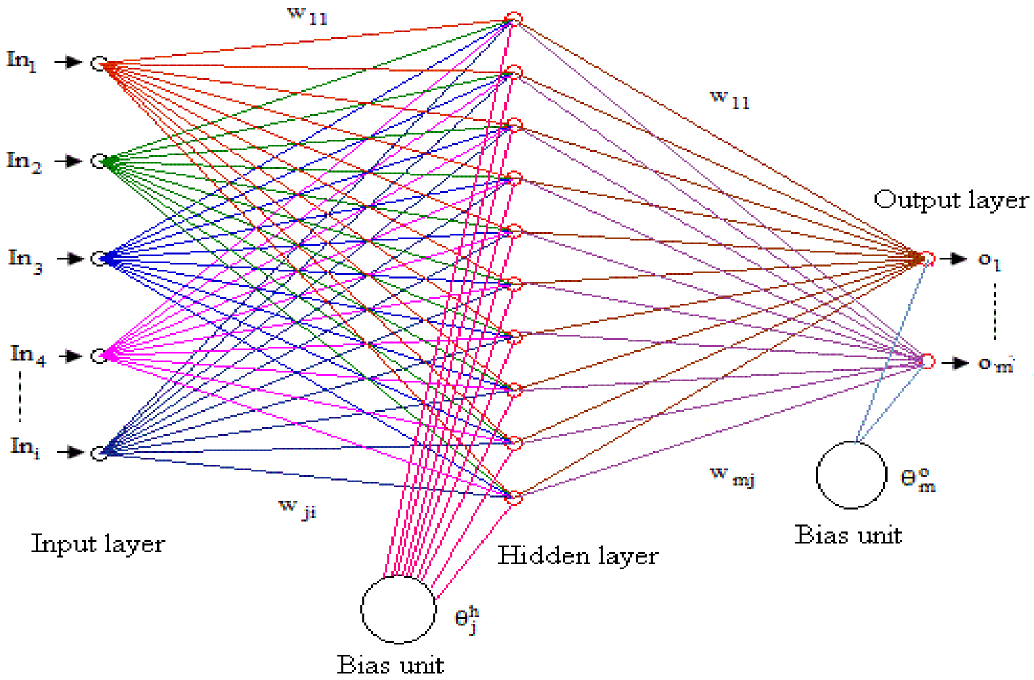

FIGURE 1: Generalized Neural Network Configuration

To address these challenges, this paper proposes a comprehensive framework that combines robust segmentation with an optimized deep learning model. The key contributions are:

1. Application of the Fuzzy Rough C-Means (FRCM) clustering algorithm for effective segmentation of diseased regions, leveraging its strength in handling uncertainty and image noise.
2. A novel hybrid classification model where the architecture of a VGG16 CNN is optimized using the Antlion Optimization (ALO) algorithm to enhance its performance for the specific task of cotton disease identification.
3. A comparative evaluation demonstrating that the proposed ALO-VGG16 model achieves superior accuracy compared to several existing methods.

The remainder of this paper is structured as follows: Section 2 details the proposed methodology, Section 3 presents the experimental results and discussion, and Section 4 concludes the work and suggests future directions.

II. PROPOSED METHODOLOGY

The proposed framework for automated plant disease detection comprises four sequential stages: Image Pre-processing, Segmentation, Feature Extraction, and Classification. The overall workflow is designed to enhance image quality, isolate the region of interest, and accurately classify the disease.

2.1 Image Acquisition and Pre-processing:

A dataset of cotton leaf images, including samples affected by Bacterial Blight, Anthracnose, Cercospora, and Alternaria, along with healthy leaves, was compiled for this study. Raw images captured in field conditions often contain noise from various sources. To improve subsequent analysis, a **Median filter** is applied in the pre-processing stage. This non-linear digital filtering technique is particularly effective at removing 'salt-and-pepper' noise while preserving the edges of the leaves and disease lesions, resulting in a cleaner image for segmentation [10, 11].

2.2 Image Segmentation using Fuzzy Rough C-Means (FRCM) Algorithm:

Accurate segmentation of the diseased lesion from the healthy leaf tissue is critical. This work employs the **Fuzzy Rough C-Means (FRCM)** clustering algorithm for this task [12, 13]. FRCM integrates the principles of fuzzy logic and rough set theory, offering advantages over conventional clustering like K-means.

- **Fuzzy Logic:** Allows pixels to belong to multiple clusters with varying degrees of membership, effectively handling the inherent ambiguity at lesion boundaries.
- **Rough Set Theory:** Models uncertainty by defining upper and lower approximations of clusters, making the algorithm more robust to noise and intensity variations within the lesion and background.

The algorithm initializes cluster centers and iteratively minimizes an objective function that factors in both the distance of pixels to cluster centers (fuzzy membership) and the roughness of the cluster approximations. Upon convergence, each pixel is assigned to the cluster with the highest membership value, producing a segmented image where the diseased region is distinctly isolated.

2.3 Feature Extraction:

Following segmentation, relevant features are extracted from the diseased region to facilitate classification. This process involves quantifying visual characteristics that distinguish one disease from another. While deep learning models automate this in later stages, the initial segmentation focuses on color, texture, and shape attributes. Color-based feature extraction, analyzing changes in color distribution (e.g., chlorosis, necrosis), is a fundamental method for identifying disease symptoms [14].

2.4 Classification using Antlion Optimization (ALO) Enhanced VGG16 CNN:

This stage constitutes the core innovation of the work, involving a hybrid model for disease classification.

2.4.1 Base Classifier: VGG16 Architecture:

VGG16 is a deep CNN model comprising 13 convolutional layers and 3 fully connected (FC) layers [Jaderberg et al., 2015]. Its deep, uniform architecture (using small 3x3 filters throughout) has proven highly effective for image recognition. We adopt VGG16 as our base classifier, modifying its final FC layer to have five neurons corresponding to our four disease classes and one healthy class.

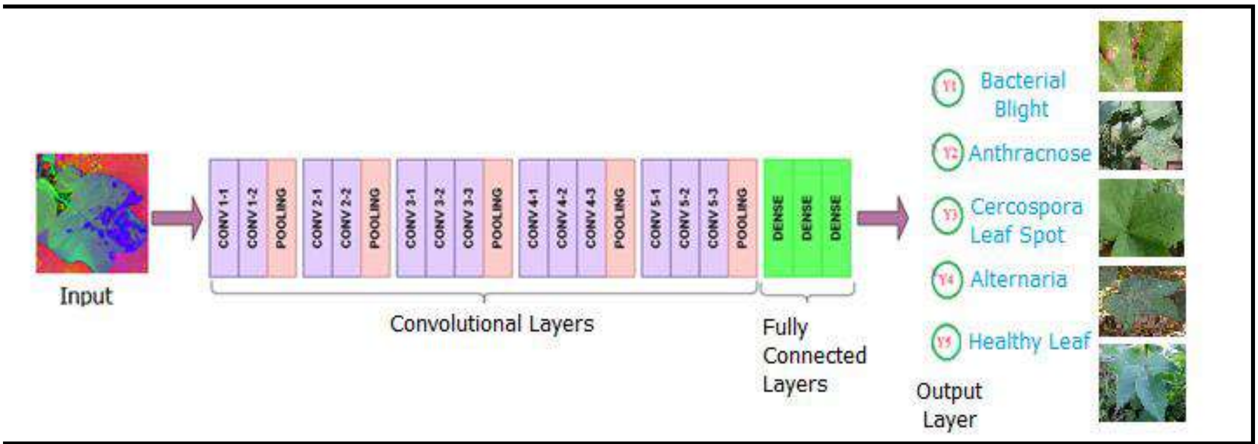

FIGURE 2: VGG16 Architecture for diseased Image Classification

2.4.2 Optimization with Antlion Algorithm (ALO):

The **Antlion Optimization (ALO)** algorithm is a nature-inspired metaheuristic that mimics the hunting mechanism of antlions in nature [15]. The process involves two main phases:

1. **Random Walk of Ants:** Represents the exploration of the search space (potential solutions).
2. **Building Traps by Antlions:** Represents the exploitation of promising areas, where better solutions (antlions) build pits to catch ants (other solutions).

In our work, ALO is employed to **optimize a key hyperparameter of the VGG16 model: the number of neurons in its first fully connected layer**. A population of candidate solutions (different neuron counts) is generated. Each candidate is evaluated by training a VGG16 model with that architecture on a subset of data and measuring its performance (e.g., validation accuracy), which serves as the fitness function. The ALO algorithm iteratively refines the population over generations, guiding the search toward the neuron count that yields the highest model fitness.

2.4.3 The ALO-VGG16 Hybrid Model:

The proposed hybrid model, termed **ALO-VGG16**, is created by integrating the optimization power of ALO into the VGG16 framework. The optimized architecture, determined by the ALO algorithm, is then fully trained on the entire training dataset. This approach tailors the deep learning model specifically to the characteristics of the plant disease image data, aiming to improve feature representation and final classification accuracy compared to the standard, non-optimized VGG16 model.

III. RESULTS AND DISCUSSION

The proposed ALO-VGG16 model was implemented and evaluated using a dataset of cotton leaf images. The model's performance was assessed using standard metrics derived from the confusion matrix: True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives (FN).

Performance Metrics:

- **Precision** (Positive Predictive Value) = TP / (TP + FP)
- **Recall** (Sensitivity) = TP / (TP + FN)
- **F1-Score** = 2 * (Precision * Recall) / (Precision + Recall)
- **Specificity** = TN / (TN + FP)
- **Accuracy** = (TP + TN) / (TP + TN + FP + FN)

3.1 Performance of the ALO-VGG16 Model:

Table 1 presents the detailed performance of the ALO-VGG16 classifier across the five classes. The model achieved high and consistent metrics for all disease types and the healthy class. The average accuracy across all classes was **93.33%**, with individual class accuracies ranging from 93.06% to 93.52%. The high F1-scores (average 93.4%) indicate a strong balance between precision and recall.

TABLE 1
CLASSIFICATION PERFORMANCE METRICS FOR ALO-VGG16

S. No	Disease	Samples	Precision	Recall	F1-Score	Specificity	Accuracy
1	Bacterial Blight	397	92.5	93.6	92.8	93.7	93.45
2	Anthracnose	340	93.4	92.9	93.2	93.1	93.52
3	Cercospora	370	92.4	93.7	93.8	92.9	93.51
4	Alternaria	392	93.5	92.7	93.4	92.7	93.11
5	Healthy	562	93.7	93.5	93.7	93.1	93.06
Average			93	93.3	93.4	93	93.33

3.2 Comparative Analysis:

To validate the efficacy of the proposed optimization, the ALO-VGG16 model was compared against several standard classifiers. The results, summarized in Table 2 and visualized in Figure 3, clearly demonstrate its superior performance.

TABLE 2
ACCURACY COMPARISON OF DIFFERENT CLASSIFIERS

Classifier	Accuracy (%)
ALO-VGG16 (Proposed)	93.33
ResNet-CNN	92.06
ANN	92.5
SVM	91
CNN	91
KNN	82.5

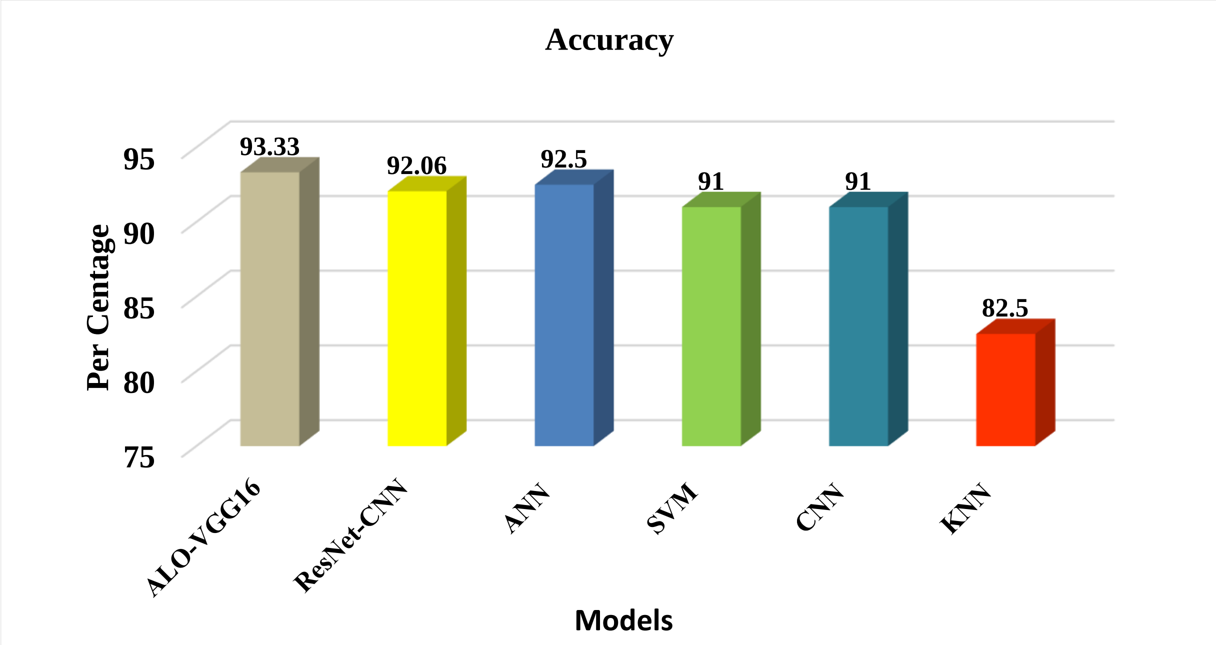

FIGURE 3: Comparative Accuracy of Various Classifiers (A bar chart would visually represent the data from Table 2).

3.3 Discussion:

The experimental results confirm the effectiveness of the proposed framework. The use of the FRCM algorithm for segmentation likely contributed to cleaner feature extraction by accurately isolating lesion boundaries despite noise. Most significantly, the integration of the Antlion Optimization algorithm with VGG16 provided a measurable boost in classification accuracy.

The ALO-VGG16 model outperformed the standard CNN (91.00% vs. 93.33%), highlighting the benefit of hyperparameter optimization. It also surpassed the more complex ResNet-CNN model (92.06%), suggesting that a well-optimized, simpler architecture can be more effective than a deeper, non-optimized one for this specific task. The superior performance over traditional machine learning models like SVM, KNN, and ANN underscores the advantage of deep learning in handling complex visual patterns in plant disease imagery.

The high accuracy and robust metrics across all classes indicate that the model is not only accurate but also reliable and generalizable within the tested dataset. The ALO algorithm successfully identified a more efficient configuration for the VGG16 network, enhancing its capability to discriminate between the subtle visual features of different cotton diseases.

IV. CONCLUSION AND FUTURE WORK

This research presented an optimized AI-based framework for the automated detection and classification of cotton leaf diseases. The methodology combined robust pre-processing using a Median filter, precise segmentation via the Fuzzy Rough C-Means (FRCM) algorithm, and a hybrid deep learning model. The key innovation was the enhancement of a VGG16 convolutional neural network using the Antlion Optimization (ALO) metaheuristic to optimize its architectural hyperparameter.

The proposed ALO-VGG16 model achieved an average classification accuracy of 93.33%, demonstrating superior performance compared to several benchmark models including standard CNN, ResNet, SVM, and ANN. This work validates that integrating nature-inspired optimization algorithms with deep learning architectures can significantly improve the precision of agricultural diagnostic systems.

For future work, the model can be tested on larger, more diverse datasets encompassing multiple crops and diseases captured under real-field conditions with complex backgrounds. Further optimization could explore tuning other hyperparameters (learning rate, filter sizes) using ALO or other metaheuristics. Finally, deploying the trained model as a user-friendly mobile application would be a practical step toward making this technology accessible to farmers for rapid, in-field disease diagnosis.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Effect of Seed Rate and Nitrogen Nutrition on Rice Fallow Finger Millet- A Review

D. Nagalakshmi[1*]; B. Rajendra kumar[2]; A. Upendra Rao[3]; J. Jagannadham[4]; S. Govinda Rao[5]

[*1]PG Student, Department of Agronomy, ANGRAU, Agricultural College, Naira
[2]Associate professor, Department of Agronomy, ANGRAU, Agricultural College, Naira
[3]Senior professor and head, Department of Agronomy, Agricultural College, Naira
[4]Professor, Department of Soil Science, Agricultural College, Naira
[5]Assistant Professor, Department of Statistics & CA, ANGRAU, Agricultural College, Naira
*Corresponding Author

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Abstract**—** *Finger millet (Eleusine coracana (L.)), a climate resilient and nutrient dense cereal, holds significant potential for sustainable intensification of rice fallow systems in India. Its rich profile of calcium, dietary fibre, and essential amino acids makes it a critical crop for addressing nutritional security, particularly in dryland and tribal regions. However, suboptimal agronomic practices, especially with regard to seed rate and nitrogen nutrition, continue to limit its productivity in rice fallow conditions.*

This review synthesizes recent research findings to evaluate the influence of seed rate and nitrogen management on the growth, yield attributes, and resource-use efficiency of finger millet. Studies indicate that appropriate seed rate enhances plant population, tillering, and weed suppression, while optimizing nitrogen levels significantly boosts chlorophyll content, dry matter accumulation, grain yield, and nitrogen use efficiency. Findings from trials conducted across diverse agro ecological zones including Zaid and summer seasons demonstrate that both excess and deficient nitrogen applications negatively affect yield and grain quality. Furthermore, the interaction between seed rate and nitrogen shows synergistic effects on canopy architecture, nutrient uptake, and panicle development, particularly under residual soil moisture conditions typical in rice fallows.

Despite extensive field experimentation, region specific recommendations for rice fallow ecosystems remain limited. This review reveals the importance of optimizing both seed rate (typically 6–15 kg/ha) and nitrogen management (60–80 kg N/ha) to unlock the genetic yield potential of finger millet and promote its adoption in underutilized rice fallow areas for greater food and nutritional security.

Keywords**— Finger millet; Eleusine coracana L.; rice fallow agriculture; seed rate optimization; nitrogen management; nutrient uptake; grain yield; growth attributes; crop productivity.***

I. INTRODUCTION

Among small millets finger millet is one of the most nutritious crops, with high levels of methionine, an essential amino acid lacking in diets of millions of poor living on starchy foods. Finger millet has been identified as one of the "future smart food crops" by FAO (Li and Siddique, 2018). Finger millet is known for drought tolerance and can adapt to a wide range of soil and climatic conditions though it prefers fertile, well drained sandy to sandy loam soils, with a pH ranging from 5 to 7 (Triveni *et al.*, 2018). It withstands warming stress, water stress and nutrition stress hence it is called "A climate change compliant crop" (Ferry, 2004). It is an important dryland millet crop and ranks third among the millet crops. In India it is widely cultivated in the states of Karnataka, Tamil Nadu, and Andhra Pradesh, often as a rice fallow crop utilizing the residual soil moisture after the harvest of transplanted paddy. In India finger millet occupies an area of 1.03 million hectares with a production of 1.30 million metric tonnes with an average national productivity of 1336 kg ha-1 (Department of Agriculture and Farmers Welfare, Govt. of India 2023-24).In Andhra Pradesh, it is an important millet crop cultivated in tribal and rainfed regions. It accounts for 0.27 lakh hectares of finger millet were planted, yielding 0.34 lakh tonnes of production and 1261 kg ha-1 of productivity in Andhra Pradesh (Directorate of Economics and Statistics, Andhra Pradesh, Government of Andhra Pradesh 2024).

Finger millet grain contains 9.8% proteins, 4.3% crude fiber, 81.5% carbohydrates, 2.7% minerals, 1.37% ash and 0.33% calcium (Amir Gull *et al.*, 2014). It also contains vitamin A, D, iron, phosphorous and dietary fibre. It is having low glycemic index and free from glutin which makes it suitable for people suffering from digestive problems, diabetes, hypertension and obesity. Silage is prepared from the green straw of finger millet. It is an eco-friendly crop which requires less nutrients. Rice-fallow finger millet makes efficient use of the remaining soil moisture and nutrients during the fallow period after rice, thus increasing yield. When traditional crops fail in rice fallows, particularly in north coastal Andhra Pradesh, farmers are interested in growing finger millet in these areas and are looking for a decent package to follow. Since nitrogen and the ideal plant population are the two most important production elements, optimizing the N dose and seed rate is crucial for rice fallow finger millet.

Nitrogen availability is the nutrient that most frequently restricts crop production, making it a crucial component of agricultural productivity. Increased levels of N application lead to increased yield attributes and grain yield (Chakraborty *et al.*, 2002). Applying the proper amount of N fertilizer is crucial for achieving the highest possible finger millet production. Variations in seed rates and nitrogen application dosages in rice fallow finger millet can impact crop growth, yield, and economics. To maintain production and profits in finger millet generally, it is essential to optimize seed rate and nitrogen application. This review aims to synthesize and evaluate current research on the effects of seed rate and nitrogen nutrition on the performance of finger millet in rice fallow systems, with the objective of identifying optimal agronomic practices and highlighting future research needs.

II. THE ROLE OF SEED RATE AND NITROGEN NUTRITION IN RICE FALLOW FINGER MILLET:

Application of the right dose of N fertilizer is important to obtain optimum yield of finger millet and thus makes its cultivation profitable. Many of the soils where finger millet is grown are deficient in N (Sagar Maitra *et al.*, 2020). Nitrogen plays a crucial role in the process of photosynthesis, synthesis of chlorophyll, amino acids and other organic compounds which contribute to building units of proteins in plants. With increase in nitrogen application, the availability of nutrients will be higher in soil and there by uptake of nutrients will be higher (Gupta *et al.*, 2012).

Adequate seed rate ensures the right number of plants per unit area. This prevents under population which leads to low yield or overcrowding which leads to competition for nutrients, water and light. Finger millet yield depends on the number of productive tillers and panicles. Optimum seed rate ensures highest grain yield and biomass yield (Nigus *et al.*, 2018). Increasing seed rate increases plant density but decreases panicle weight beyond optimum levels. Higher seed rate gave higher quantitative yield attributes such as straw yield, panicle yield and grain yield. Bellatore *et al.* (1985) and Kumpawt *et al.* (1998) reported increased in straw yield with increased seed rate. Kumar *et al.* (2008) observed that seed rate increases plant density, and can compensate for reduction in plant productivity. Spanner *et al.* (2005) found that grain yield increased significantly with increasing seed rate.

III. EFFECT OF SEED RATE ON FINGER MILLET PERFORMANCE:

Optimizing seed rate is critical for enhancing the performance of finger millet, especially under resource constrained conditions like rice fallows. Chaturvedi *et al.* (2025) revealed that seed rate of 1.5 kg ha^{-1} strongly influences growth traits increases plant height (128.87cm), total number of tillers (78.88 m -2), leaf area (61.80 cm2) and dry matter accumulation per plant (27.21g). Seed rate significantly affects germination, early seedling vigour, intra-plant competition, and ultimately influences the crop's productivity and resource-use efficiency. Nigus *et al.* (2018) revealed that 15 kg ha-1 of seed rate recorded highest grain yield (2214.4 kg ha-1) and biomass yield (12889 kg ha−1).

Dereje *et al.* (2017) conducted experiment over two years at two locations and evaluated finger millet response to three seed rates (5,15,25 kg ha−1) and concluded that 15 kg ha−1 is the most suitable seed rate for highest grain yield (1926.8 kg ha−1). Bitew *et al.* (2014) conducted field experiment on effect seed rate on the growth, yield and yield component of finger millet and concluded that 10 kg ha−1 seed rate gave optimal grain yield. Opale *et al.* (2013) conducted field experiment and evaluated seeding rate of 3.2,6.0 and 9.0 kg ha−1 and stated that high seeding rate (6.0 kg ha−1) increased leaf dry weight and grain yield. Gani *et al.* (2016) conducted field experiment and evaluated three seed rates (3,6 and 9 kg ha−1) and stated that the seed rate (6.0 kg ha−1) gave highest grain yield ha−1. Hulakund *et al.* (2024) concluded that seed rate of 7.5 kg ha−1 optimizes the yield (585.6 kg ha−1) and nutrient uptake.

TABLE 1
SUMMARY OF RESEARCH ON THE EFFECT OF SEED RATE ON FINGER MILLET PERFORMANCE

Study (Author, Year)	Location / Context	Seed Rates Evaluated (kg ha⁻¹)	Optimal Seed Rate Identified (kg ha⁻¹)	Key Outcome / Yield at Optimal Rate
Chaturvedi *et al.* (2025)	Not specified	1.5	1.5	Max. plant height, tillers, leaf area, dry matter.
Nigus *et al.* (2018)	Not specified	15	15	Highest grain yield (2214.4 kg ha⁻¹) & biomass.
Dereje *et al.* (2017)	Two locations over 2 years	5, 15, 25	15	Most suitable for highest grain yield (1926.8 kg ha⁻¹).
Bitew *et al.* (2014)	Field experiment	Varied	10	Gave optimal grain yield.
Opale *et al.* (2013)	Field experiment	3.2, 6.0, 9.0	6	Increased leaf dry weight and grain yield.
Gani *et al.* (2016)	Field experiment	3, 6, 9	6	Gave the highest grain yield per hectare.
Hulakund *et al.* (2024)	Not specified	7.5	7.5	Optimized yield (585.6 kg ha⁻¹) and nutrient uptake.
Reported Range	**Across diverse agro-ecologies**	**1.5 - 25**	**15-Jun**	**Most common optimal range for grain yield.**

Note: Data presented in this table are synthesized from the experimental results of the referenced studies reviewed in the preceding text.

IV. EFFECT OF NITROGEN NUTRITION ON THE PERFORMANCE OF FINGER MILLET:

Nitrogen is a key macronutrient in plant nutrition, playing a crucial role in various physiological and biochemical processes. Nitrogen fertilizer is one of the most yield limiting nutrients for crop production and it is applied in large quantity for most annual crops (Huber and Thompson, 2007). In finger millet (Eleusine coracana L.), nitrogen influences growth, dry matter production and yield under rainfed conditions (Hari Prasanna *et al.*, 2016). The significant improvement in yield attributes was observed with application of 90 kg N ha-1 over that of lower levels ultimately increase yield. Increased uptake of N with increased levels of N application has been reported by (Sudhakar Rao *et al.*, 1991). Optimizing nitrogen levels is especially important in marginal environments like rice fallows, where soil fertility is typically low and moisture availability is limited. The studies on N fertilization indicate that higher grain yield was obtained with application of N ranging from 0 to 90 kg (Bekele *et al.*, 2016, Nigade *et al.*, 2011).

Ramyasri *et al.* (2019) concluded that application of 80 kg N ha-1 increases plant height (153.9 cm), dry matter production (3590 kg), panicles m -2(70), panicle length (16.3 cm), test weight (2.68 g), grain yield (1684 kg ha-1), straw yield (3101 kg ha-1). Bhomte *et al.* (2016) concluded that plant height (80.8 cm) was found to be increased with increased levels of nitrogen (20, 40, 60 and 80 kg ha-1). Bekele *et al.* (2016) stated that the highest plant height (70.75 cm) of finger millet was reported with 69 kg N ha-1. Navya Jyothi *et al.* (2016) stated that application of 50 kg N ha-1 increases tillers plant-1 (2.56), dry matter production (4069 kg ha-1). Rashmi Yadav *et al.* (2010) concluded that application of 60 kg N ha-1 increases tillers plant-1 (2.9), test weight (4.5 g).

Muneendra Babu *et al.* (2003) concluded that application of 50 kg N ha-1 increases ear head weight (8.5 g). Munirathnam and Kumar (2015) concluded that application of 80 kg N ha-1 increases harvest index (51.3%).Vijayamahantesh *et al.* (2016) revealed that significantly lower weed dry weight o.25 m -2 (39 g), lowest weed count m -2(17.7) of finger millet is recorded when fertilized with 100% N through urea. Krishna *et al.* (2020) reported that increasing nitrogen up to 60 kg/ha enhanced plant height, number of tillers, and biomass accumulation in finger millet during summer. The increased photosynthetic surface area led to better dry matter partitioning. Sneha *et al.* (2024) found that applying 100% recommended dose of fertilizer twice at 35 and 55 days after sowing recorded significantly higher grain yield (3453 kg ha-1) and straw yield (5035 kg ha-1). Sial *et al.* (2024) concluded that application of 80 kg N ha-1 gave highest number of tillers (5.7 hill-1), number of fingers (7.7 ear head-1), finger length (8.4 cm) and grain yield (2399 ha-1).

TABLE 2
SUMMARY OF RESEARCH ON THE EFFECT OF NITROGEN NUTRITION ON FINGER MILLET PERFORMANCE

Study (Author, Year)	N Rates Evaluated (kg N ha^{-1})	Optimal N Rate Identified (kg N ha^{-1})	Key Growth & Yield Parameters Enhanced
Ramyasri *et al.* (2019)	Up to 80	80	Plant height, dry matter, panicles m^{-2}, grain & straw yield.
Bhomte *et al.* (2016)	20, 40, 60, 80	80 (for height)	Plant height.
Bekele *et al.* (2016)	Up to 69	69	Plant height.
Navya Jyothi *et al.* (2016)	50	50	Tillers plant^{-1}, dry matter production.
Rashmi Yadav *et al.* (2010)	60	60	Tillers plant^{-1}, test weight.
Muneendra Babu *et al.* (2003)	50	50	Ear head weight.
Munirathnam & Kumar (2015)	80	80	Harvest index.
Krishna *et al.* (2020)	Up to 60	60	Plant height, tiller number, biomass.
Sneha *et al.* (2024)	100% RDF (Split)	100% RDF (Split)	Grain yield (3453 kg ha^{-1}), straw yield.
Sial *et al.* (2024)	Up to 80	80	Tillers hill^{-1}, fingers earhead^{-1}, grain yield.
Satya *et al.* (2023)	80	80	Plant height, tillers, dry weight, seed & straw yield, HI.
Sanjana *et al.* (2020)	Up to 120	120	Plant height, tillers, ears, ear weight, grain & straw yield.
Gangothri *et al.* (2023)	60	60	Plant height, tillers plant^{-1}, grain & straw yield, HI.
Ghosh *et al.* (2024)	60	60	Seed yield (18.59 q ha^{-1}), straw yield.
Jyostna *et al.* (2015)	120 (Split)	120 (Split)	Grain yield (+40%), grain quality, soil fertility.
Vamsikrishna *et al.* (2019)	90	90	Earhead weight.
Synthesized Optimal Range	**Varied (0-120)**	**60 - 80**	**Consistently improves yield, biomass, and key attributes.**

Note: Data presented in this table are synthesized from the experimental results of the referenced studies reviewed in the preceding text.

Satya *et al.* (2023) concluded that the higher plant height (79.76 cm), number of tillers plant-1 (7.85 plant-1), plant dry weight (25.92 g plant-1), seed yield (3.25 t ha-1), straw yield (4.81 t ha-1) and harvest index (40.34%) were significantly influenced with application of nitrogen 80 kg ha-1. Sanjana *et al.* (2020) stated that the highest plant height (131.7 cm), number of tillers (4 plant−1), number of ears (97.8 m -2), ear head weight (7.11 g), grain yield (2657 kg ha−1) and straw yield (3721 kg ha−1) were recorded with application of N @120 kg N ha−1. Gangothri *et al.* (2023) concluded that application of 60 kg N ha-1 recorded higher plant height (86.27 cm), number of tillers per plant (8.67 plant-1), plant dry weight (23.41), grain yield (2,635.65 kg ha1), straw yield (4883.10 kg ha-1) and harvest index (35.05). Ghosh *et al.* (2024) revealed that applying 60 kg N ha^{-1} significantly enhanced seed yield (18.59 q ha-1) and straw yield (26.04 q ha-1) of finger millet, suggesting this rate as optimal for achieving higher productivity in the coastal region of West Bengal. Jyostna *et al.* (2015) stated that applying 120 kg N ha-1 in three splits (25% basal, 50% at 30 days after transplanting, 25% at 45 days after transplanting) significantly increased grain yield (40%), quality of grain and fertility status of irrigated white grain finger millet on sandy loam soils. Vamsikrishna *et al.* (2019) concluded that significantly highest earhead weight (6.1 g) was obtained from application of 90 kg N ha-1.

V. CONCLUSION AND FUTURE PERSPECTIVES:

Based upon the reviewed literature, optimal seed rate (typically 6–15 kg/ha) improves plant population, tillering, canopy structure, and weed suppression in rice fallow finger millet. Nitrogen application (60–80 kg/ha) significantly enhances growth, chlorophyll content, dry matter accumulation, and grain yield. Both over and under application of nitrogen adversely affect yield and grain quality. A synergistic effect of seed rate and nitrogen improves nutrient uptake, panicle development, and resource use efficiency under residual moisture conditions.

TABLE 3
SYNTHESIS OF AGRONOMIC RECOMMENDATIONS FOR RICE FALLOW FINGER MILLET

Agronomic Factor	Optimal Range	Primary Effect / Benefit	Key Consideration for Rice Fallow
Seed Rate	**6 - 15 kg ha⁻¹**	• Ensures optimal plant population.	Higher end of range may be beneficial in regions with better residual moisture. Lower rates may suffice in moisture-stressed conditions to reduce competition.
		• Enhances tillering & canopy cover for weed suppression.	
		• Maximizes grain & biomass yield.	
Nitrogen Nutrition	**60 - 80 kg N ha⁻¹**	• Boosts chlorophyll synthesis & photosynthesis.	Application must be synchronized with residual soil moisture. Split applications are often crucial for improving Nitrogen Use Efficiency (NUE) in this system.
		• Increases dry matter accumulation & panicle development.	
		• Significantly enhances grain yield & harvest index.	
Synergistic Interaction	**Optimal Seed Rate + Optimal N**	• Improves nutrient uptake efficiency.	The positive interaction is critical for unlocking full genetic potential under the residual moisture and fertility constraints of rice fallows.
		• Optimizes canopy architecture for light interception.	
		• Leads to superior panicle development and final yield.	

Source: Authors' synthesis based on the consensus and ranges derived from the reviewed literature presented in this article.

To maximize productivity in rice fallows, region specific, integrated agronomic packages and precision nitrogen management are essential. Future research should focus on: (1) developing location-specific recommendations based on soil fertility and residual moisture levels, (2) investigating the interaction effects of seed rate and nitrogen across different cultivars and environments, (3) exploring efficient nitrogen sources and application timings for rice fallow systems, (4) assessing the economic viability of optimized practices for farmer adoption, and (5) integrating seed rate and nitrogen management with other agronomic practices for sustainable intensification of rice fallow finger millet cultivation

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Influence of Industrial Wastewater Irrigation on Agricultural Crops: A Comprehensive Review of Effects on Growth, Physiology, and Metabolism

Dr. Anuradha Mehta[1*]; Dr. Nagendra Bhardwaj[2]

[*1]Department of Botany, S.S.Jain Subodh P.G. College, Jaipur, India
[2]Department of Botany, University of Rajasthan, Jaipur
*Corresponding Author

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Abstract— *Industrial wastewater, containing a complex mixture of organic and inorganic compounds, exerts a profound influence on crop physiology. When pollutant concentrations are managed through dilution or treatment, the agricultural reuse of this wastewater can promote sustainable practices by conserving scarce freshwater resources and providing valuable nutrients. However, irrigation with untreated or highly concentrated effluent leads to the accumulation of toxic heavy metals in plants, adversely affecting seed germination, plant growth, crop yield, and ultimately human health. This review synthesizes current research on the quality of wastewater from diverse industries and its differential effects on growth, yield, and key physiological and biochemical parameters in various crop plants. The analysis underscores that careful, context-specific management is imperative to harness benefits while mitigating significant ecological and agricultural risks.*

Keywords— Industrial wastewater, plant growth, chlorophyll, heavy metals, oxidative stress, seed germination, genotoxicity.

I. INTRODUCTION

Environmental pollution poses a multifaceted threat with local, regional, and global impacts, significantly endangering the health of humans, animals, and plants (1). Aquatic ecosystems are particularly vulnerable, with most water sources contaminated by substantial volumes of domestic sewage and industrial effluent. Wastewater from different industries varies greatly in composition, containing substances ranging from simple nutrients to highly toxic compounds and heavy metals, making treatment both complex and costly.

In arid and semi-arid regions, wastewater is increasingly considered a vital resource for irrigation and fertilization (2). Its use in agriculture can contribute to soil conservation and waste disposal, with many effluents and sludges containing nutrients that enhance soil fertility and crop production (3). Globally, wastewater irrigation is practiced for three primary purposes: (a) as a method of effluent disposal (4); (b) as a source of plant nutrients (4); and (c) as a strategy to alleviate water scarcity for agriculture (5). This practice presents a dualistic set of consequences. Positive implications include employment generation, improved food security, a reliable irrigation supply, and nutrient recycling. Conversely, long-term use can degrade soil health through salinization, heavy metal accumulation, and structural breakdown, ultimately restricting crop choice and reducing yields.

Given these competing merits and demerits, a critical evaluation of the toxic effects of effluents and their suitability for irrigation is essential. This review article comprehensively examines the impact of various industrial wastewaters on a wide range of crop plants and soil characteristics, analyzing effects from seed germination to cellular metabolism.

II. PHYSICOCHEMICAL PROPERTIES OF INDUSTRIAL WASTEWATER

The principal constraint on expanding wastewater use for irrigation is its highly variable quality. Effluents from different industrial sources possess distinct chemical compositions, leading to disparate effects on plants. For instance, textile industry wastewater is reported to have variable pH, high electrical conductivity (EC), significant levels of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^{-}, CO_3^{2-}, Cl^{-}), and often heavy metals like Zn, Cu, Cr, Pb, Mn, Ni, and Fe. Sugar mill effluents are typically characterized by high biological and chemical oxygen demand (BOD and COD) (6,7), which can deplete aquatic oxygen and reduce biodiversity. Elevated EC, indicative of high dissolved ion concentrations, is a common feature of sewage and industrial wastewater (8). The carbon content and the balance of organic and inorganic constituents also vary with the source and treatment level. This variability means that while wastewater can be a valuable source of irrigation water and nutrients for farmers' fields, its specific composition must be the primary determinant of its use.

III. EFFECTS ON SEED GERMINATION AND SEEDLING GROWTH

The presence of various chemicals in wastewater often detrimentally affects early plant development. Research demonstrates that the impact varies significantly both by effluent type and crop species. A linear decrease in germination percentage, speed, and germination value has been noted in vegetables like tomato, chilli, and onion when irrigated with effluent from petroleum refineries, paper mills, ordnance factories, and distilleries.

Gulfraz et al. (9) evaluated the suitability of different industrial effluents for wheat irrigation, finding seed germination was most severely affected by textile mill wastewater, followed by soap and detergent, oil refinery, hydrogenated oil, and rubber industry effluents. This study concluded that untreated wastewaters should not be discharged into agricultural systems and advocated for industrial treatment plants. Similarly, Karunyal et al. (10) reported a decline in germination, chlorophyll, and protein content in *Oryza sativa* with increasing concentrations of tannery effluent.

Conversely, studies also show the potential benefits of properly managed effluent. Kalaiselvi et al. (11) found that distillery spentwash at concentrations up to 10% improved seed germination and seedling growth in maize, suggesting its safe use as a fertilizer substitute after appropriate dilution. Singh et al. (12) observed that fertilizer factory effluent at 25% concentration could increase root/shoot length and chlorophyll content in gram (*Cicer arietinum*) after 21 days, though higher concentrations were toxic. These studies collectively affirm that the effects on germination and early growth are critically dependent on effluent source, concentration, and crop tolerance.

IV. EFFECTS ON CROP GROWTH, BIOMASS, AND YIELD

Wastewater-induced plant damage typically results from a combination of osmotic stress and specific ion toxicity (13, 14). A major concern is the accumulation of trace elements (e.g., Pb, Cd, Ni) and microbial pathogens, which can degrade soil physical conditions and food safety (15). Despite these risks, many studies report growth and yield enhancements with wastewater application, primarily due to its nutrient content.

Garg and Kaushik (16) noted increased plant height and biomass in certain crops with diluted (6.25%) textile mill effluent. In sugarcane, spentwash application boosted yield and available nitrogen in soil (17). Research on rice indicates that distillery spentwash diluted 50 to 100 times can produce normal or even maximum grain yields (18, 19). However, inhibitory effects are clear with untreated effluents. Mohana et al. (20) reported that untreated coffee wastewater reduced plant height, tiller number, leaf area, dry matter, chlorophyll, and nutrient content in Palmarosa grass, while treated effluent performed better.

The nature of the effluent defines its impact. Giovacchino et al. (21) found that olive vegetable water (OVW) applied at over 10 L m^{-2} increased total maize biomass by 30-40%. In contrast, crops produced with heavy metal-contaminated effluent often show poor growth and reduced shelf life (22). Sewage-irrigated crops may exhibit vigorous vegetative growth due to excess nitrogen but often have lower economic yield (23). Akhtar et al. (24) demonstrated that thermal power plant wastewater could enhance growth, photosynthesis, seed yield, and oil content in mustard and linseed when combined with balanced NPK fertilization, presenting it as a viable irrigation alternative. Shukry et al. (25) have reported increase in soluble nitrogen content in wheat grains when irrigated with industrial effluents.

V. EFFECTS ON PHOTOSYNTHETIC PIGMENT CONTENT

Photosynthetic pigments are highly sensitive to pollution stress. Under effluent-induced stress, chlorophyll can undergo photochemical reactions like oxidation, reduction, and pheophytinization, altering plant physiology and biochemistry (26).

Studies consistently show pigment reduction under effluent stress. Akujobi et al. (27) reported decreased chlorophyll and protein in eggplants due to diesel oil pollution. Nath et al. (28) observed significant reductions in chlorophyll, pheophytin, and carotenoids in *Phaseolus mungo* with tannery effluent and Cr^{2+}. Bamniya et al. (29) found similar decreases in chlorophylls and carotenoids in *Brassica oleracea* and *Spinacia oleracea* irrigated with mixed industrial-municipal wastewater.

Kakar et al. (30) provided a detailed physiological analysis, showing that municipal wastewater reduced stomatal conductance, transpiration rate, and photosynthetic rate by up to 69% in canola. Chlorophyll *a* and *b* were reduced by 68-86%, with the higher-concentration effluent (100%) causing the most severe damage. This direct impairment of the photosynthetic apparatus is a primary mechanism behind the observed growth reductions.

VI. EFFECTS ON METABOLISM, PROTEIN CONTENT, AND OXIDATIVE STRESS

Industrial effluents often induce metabolic stress, triggering the production of reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, and hydroxyl radicals (31, 32). These ROS can damage DNA, proteins, chlorophyll, and cellular membranes. Plants activate complex enzymatic and non-enzymatic antioxidant systems, including superoxide dismutase (SOD), catalase (CAT), peroxidase, and ascorbic acid, to mitigate this oxidative damage (33).

Elevated antioxidant activity is a common biomarker of effluent stress. Studies report increased catalase (34), peroxidase (28), and ascorbic acid (35) activities under heavy metal stress. Sangeetha et al. (36) documented a significant increase in SOD, CAT, and glutathione peroxidase (GPx) activity in maize seeds exposed to undiluted textile effluent, with a less drastic increase under diluted effluent treatment. This indicates that the plant's antioxidant defense system is engaged proportionally to the stress level, and its capacity can be overwhelmed by high concentrations of pollutants.

VII. EFFECTS ON CELL DIVISION AND GENOTOXICITY

Wastewater irrigation can directly harm fundamental cellular processes. Effluents often reduce mitotic division rates in root meristems and induce chromosomal aberrations such as spindle defects, lagging chromosomes, fragments, and irregular chromosome distribution (37, 38).

Kara et al. (39) observed a decreased mitotic index in *Allium cepa* root tips exposed to industrial water samples from the Gediz River area. Srivastava and Jain (40) reported a 63% to 100% decline in mitotic efficiency in sugarcane root meristems treated with crude spentwash. The cytotoxic and genotoxic effects included spindle inhibition, chromosome stickiness, C-mitosis, multipolarity, and micronuclei formation. These effects are frequently attributed to heavy metals (e.g., Cr, Ni, Cd) in the effluent, which can cause oxidative DNA damage and disrupt spindle apparatus function (41). The inhibition of DNA synthesis or cellular energy (ATP) production are potential mechanisms behind this mitodepression (42, 43).

VIII. NUTRIENT AND HEAVY METAL ACCUMULATION IN CROPS

The nutrient content of wastewater can improve soil fertility and crop yield, acting as a slow-release fertilizer rich in N, P, K, and micronutrients (44). Ouazzani et al. (45) found that wastewater-irrigated meadows received N and P at or above recommended fertilizer rates.

However, improper management leads to excessive nutrient and heavy metal accumulation in plants, reducing yield quality and introducing toxins into the food chain (46, 47). The bioavailability and translocation of metals vary significantly. For example, Cd can accumulate in edible parts at levels hazardous to consumers without harming the crop itself, whereas Pb and Cr are less plant-available (48, 49). Metal distribution within the plant also differs; Ni tends to accumulate in roots, while Fe, Mn, and Cu are more mobile and accumulate in shoots (50, 51). Antagonistic interactions between ions can also affect uptake; for instance, high Zn^{2+} and Mn^{2+} can depress Fe^{3+} absorption (52, 53, 54), and the translocation of Zn^{2+} and Ni^{2+} from roots to shoots is often limited (55).

IX. CONCLUSION AND FUTURE PERSPECTIVES

This comprehensive review confirms that industrial wastewater reuse in agriculture presents a complex trade-off between significant benefits and serious risks. The body of research indicates that with proper dilution and pre-treatment, certain effluents can be a valuable source of water and nutrients, enhancing crop growth and yield. Conversely, untreated or concentrated wastewater leads to toxic effects including suppressed germination, reduced growth and photosynthetic efficiency, oxidative stress, genotoxicity, and the accumulation of heavy metals in edible tissues, posing a direct threat to ecosystem and human health.

Therefore, a universal endorsement of wastewater irrigation is not feasible. Its suitability is entirely context-specific, depending on the effluent's chemical profile, the degree of dilution or treatment, the crop species, and soil characteristics. A thorough economic and environmental impact analysis is prerequisite for any large-scale implementation. Future research should prioritize: 1) Long-term field studies on soil-pollutant-plant transfer dynamics; 2) The development of cost-effective, industry-specific tertiary treatment technologies; and 3) The breeding and selection of crop varieties with greater tolerance to common wastewater pollutants. Ultimately, rigorous, science-based guidelines and continuous monitoring are essential to harness the potential of this resource while safeguarding agricultural sustainability and public health.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Soil Degradation as a Planetary Threat to Agricultural Productivity and Long-Term Food Security: A Global Synthesis of Impacts and Rehabilitation Strategies

Dr. Sajid Farid[1*]; Saadia Razzaq[2]; Muhammad Abdullah Sajid[3]

[*1]Section Manager, Agri. Services, FFC Pakistan
[2]Saadia Razzaq, Associate Professor, HOD Department of Education, Islamabad Model College for Girls F-7/4 Islamabad Pakistan & PhD Scholar, International Islamic University Islamabad, Pakistan.
[3]Muhammad Abdullah Sajid, School of Electrical Engineering and Computer Science, National University of Science and Technology, (SEECS-NUST), Islamabad, Pakistan
*Corresponding Author

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Abstract— *Soil degradation—including erosion, salinization, nutrient depletion, organic-matter decline, and biodiversity loss—has emerged as one of the most urgent threats to agricultural productivity and long-term food security. This paper provides an integrative global synthesis, analyzing the interconnected biophysical and socio-economic dimensions of soil degradation and evaluating the effectiveness of large-scale rehabilitation responses. We find that nearly 33% of the Earth's soils are degraded, directly impacting 1.7 billion people through reduced yields. Projections indicate that 90% of soils could be degraded by 2050, risking US$23 trillion in economic losses. However, our analysis of major global restoration initiatives reveals that degradation is reversible. Success hinges on integrating science-based practices (e.g., agroforestry, terracing) with strong policy support and community engagement. This synthesis underscores that safeguarding soil health is not merely an agronomic concern but a foundational prerequisite for achieving global food security and sustainable development goals. Coordinated action to scale up proven soil-rehabilitation models is urgently needed.*

Keywords— Soil degradation, Soil erosion, Salinization, Food security, Sustainable soil management, Land restoration, Rehabilitation.

I. INTRODUCTION

Soil is the foundational resource for global food systems, supporting nearly 95% of the world's food production. As a living ecosystem, it regulates plant growth, water filtration, carbon storage, and nutrient cycling. Yet, this critical resource is deteriorating at an unprecedented rate due to intensive agriculture, deforestation, unsustainable irrigation, industrial pollution, and climate change. Globally, an estimated 33% of soils are moderately to highly degraded, with over half of agricultural land degraded in some regions.

The consequences are profound: declining soil fertility, loss of topsoil, and reduced organic matter directly undermine crop yields and resilience. Recent assessments indicate that 1.7 billion people live in areas where soil degradation has reduced crop yields by at least 10%. Economically, the cost of inaction is staggering, with projected losses of up to US$23 trillion by 2050.

While the scope of the crisis is well-documented, there is a pressing need for integrated analyses that connect the dots between the global extent of degradation, its multifaceted impacts on food security, and the practical lessons from large-scale rehabilitation efforts. This study addresses that gap. We synthesize global evidence to: (1) quantify the interconnected drivers and impacts of soil degradation, (2) critically evaluate the outcomes of major soil-restoration initiatives worldwide, and (3) derive transferable principles for effective policy and management. By linking problem diagnosis with solution analysis, this paper aims to inform strategic investments and actions to reverse soil degradation and secure resilient food systems.

Objectives of the Study:

1. To examine the global extent, drivers, and interlinked types of soil degradation affecting agricultural lands.
2. To analyze the direct and indirect impacts of soil degradation on food security at regional and global scales.
3. To evaluate the effectiveness, methodologies, and contextual factors of major soil-rehabilitation initiatives implemented worldwide.
4. To identify sustainable soil management practices and policy frameworks that can mitigate degradation and promote long-term agricultural resilience.
5. To provide evidence-based recommendations for scaling up successful restoration models.

II. MATERIALS AND METHODS

This study employed a systematic, integrative review methodology to synthesize evidence from soil science, agricultural economics, and environmental policy. The review protocol was designed to ensure reproducibility and comprehensiveness.

2.1 Literature Search and Selection:

A systematic search was conducted across academic databases (ScienceDirect, JSTOR, Google Scholar) and institutional repositories (FAO, UNCCD, UNEP, World Bank) for literature published between 2007 and 2024. Search strings combined key terms: ("soil degradation" OR "land degradation") AND ("food security" OR "agricultural productivity"); ("soil erosion" OR "salinization") AND ("impact" OR "yield loss"); ("soil restoration" OR "sustainable land management") AND ("case study" OR "effectiveness").

2.2 Inclusion/Exclusion Criteria:

Included sources: (1) peer-reviewed articles and major institutional reports containing global or regional empirical data on soil degradation extent or impact; (2) studies analyzing the linkage between soil health and food security indicators; (3) documented evaluations of large-scale rehabilitation programs (e.g., Great Green Wall, Loess Plateau). Excluded sources: non-English publications, editorials without new data, and studies lacking clear methodological description.

2.3 Screening and Data Extraction:

The initial search yielded over 500 records. After removing duplicates and screening titles/abstracts, 152 full-text sources were assessed for eligibility. A final set of 89 sources met all inclusion criteria. Data were extracted into a standardized matrix, capturing: geographic scope, degradation type, quantitative impacts, rehabilitation methods, and reported outcomes.

2.4 Quality Appraisal and Synthesis:

Source quality was appraised based on methodological rigor, data transparency, and institutional authority. Priority was given to meta-analyses, long-term studies, and FAO/UNCCD flagship reports. A narrative synthesis approach was used, guided by the study objectives. Findings were thematically grouped to first establish the state of degradation (Results), then critically analyze impacts and rehabilitation strategies (Discussion). Cross-case comparison was used to distill lessons from different restoration initiatives.

III. RESULTS

3.1 Global Extent and Severity of Soil Degradation:

Global assessments confirm a soil crisis of planetary scale. Approximately 33% of global soils are moderately to highly degraded, with critical regions like Sub-Saharan Africa and South Asia experiencing degradation on over 50% of agricultural land. Soil erosion is the most widespread process, stripping an estimated 24 billion tons of fertile topsoil annually—a rate far exceeding natural formation. Salinization affects over 833 million hectares, primarily in irrigated zones. Concurrently, soil organic matter (SOM)—a key indicator of health—has declined by 25-40% in intensively farmed regions, undermining soil structure and biological activity (Table 1).

TABLE 1
GLOBAL EXTENT AND KEY INDICATORS OF SOIL DEGRADATION

Indicator	Global Estimate	Most Affected Regions	Primary Source
Total degraded soils	~33% of global soils	Sub-Saharan Africa, South Asia, Latin America	FAO (2015)
Annual soil erosion loss	24 billion tons	East Asia, South America, Africa	UNCCD (2020)
Salt-affected soils	833 million hectares	Central Asia, Indo-Gangetic Plains, Australia	FAO (2021)
Decline in Soil Organic Matter	25-40% loss in intensive systems	Europe, North America, South Asia	Gomiero (2016)
Population affected by yield loss	1.7 billion people (≥10% loss)	Africa, Asia	FAO (2023)
Projected economic cost by 2050	US $23 trillion in losses	Global projection	FAO (2022)

3.2 Impacts on Agricultural Productivity and Food Security:

The degradation of soil properties has direct, quantifiable impacts on crop production. Erosion and SOM loss reduce yields by 10-50% in severely affected areas. Salinization can render land completely unproductive. Degraded soils also exhibit reduced water-holding capacity, amplifying crop vulnerability to drought and flooding. These biophysical impacts cascade into the food system, reducing food availability, increasing production costs and price volatility, and threatening the livelihoods of smallholder farmers (Table 2). The economic and social burdens are disproportionately borne by food-insecure populations, directly contravening SDG 2 (Zero Hunger).

TABLE 2
KEY PATHWAYS FROM SOIL DEGRADATION TO FOOD INSECURITY

Degradation Process	Biophysical Impact	Food Security Consequence	Evidence
Erosion & SOM Decline	Loss of nutrients, poor water retention	Reduced yields (10-50%), lower food availability	UNCCD (2020); FAO (2019)
Salinization	Toxicity, reduced germination	Loss of arable land, collapse of farm income	FAO (2021)
Compaction	Restricted root growth	Lower crop yields, increased drought stress	UNEP (2022)
Nutrient Depletion	Imbalanced soil chemistry	Rising fertilizer dependency & costs	FAO (2015)
Biodiversity Loss	Weak nutrient cycling & pest control	Unstable, input-dependent production	Barrios (2007)

3.3 Overview of Global Rehabilitation Initiatives:

Large-scale programs demonstrate that soil degradation is reversible. Key initiatives, their methods, and reported outcomes are summarized in Table 3. These examples form the basis for the comparative analysis in the following Discussion section.

TABLE 3
MAJOR GLOBAL SOIL REHABILITATION INITIATIVES

Initiative	Region	Core Methods	Reported Outcomes
Great Green Wall	Sahel, Africa	Agroforestry, FMNR, water harvesting	20M+ ha restored, increased incomes, improved resilience
Loess Plateau Rehab.	China	Terracing, reforestation, grazing bans	Sediment runoff ↓70%, 2.5M people lifted from poverty
EU Soil Mission	European Union	Carbon farming, soil monitoring, decontamination	Target: 75% healthy soils by 2030
FAO Global Soil Partnership	Global	Soil Doctors training, SSM guidelines	Enhanced national soil information capacities
Regenerative Agriculture	Global (e.g., LatAm, Africa)	No-till, cover crops, agroforestry	Increased SOM, improved soil structure, reduced erosion

IV. DISCUSSION AND SYNTHESIS

4.1 Interconnected Degradation and Compounding Risks:

Our synthesis confirms that soil degradation processes rarely occur in isolation. For example, erosion leads to SOM and nutrient loss, which in turn increases susceptibility to compaction and acidification. This interplay creates compounding risks that are greater than the sum of individual threats. Furthermore, climate change acts as both a driver and a multiplier of degradation, intensifying water stress and erosion rates. This interconnectedness necessitates holistic management strategies that address multiple soil functions simultaneously, rather than single-issue interventions.

4.2 Critical Analysis of Rehabilitation Pathways:

The case studies in Table 3 reveal common success factors and context-specific challenges, analyzed comparatively in Table 4.

TABLE 4
COMPARATIVE ANALYSIS OF REHABILITATION INITIATIVES: SUCCESS FACTORS AND CHALLENGES

Initiative	Key Success Factors	Major Challenges & Trade-offs
Great Green Wall	**Community-led design**, use of native species, dual focus on ecology & livelihoods	**Long-term funding**, scaling beyond pilot sites, tenure security for farmers
Loess Plateau	**Strong top-down policy** (grazing bans), major **public investment** in terracing	**Less community input** in early stages, high initial capital cost
EU Soil Mission	**Robust monitoring framework**, integration with **CAP subsidy incentives**	**Complex bureaucracy**, reliance on voluntary farmer adoption
Regenerative Agriculture	**Farmer-to-farmer knowledge sharing**, builds on local innovation	**Lack of standardized metrics**, short-term yield dips can deter adoption

The **Great Green Wall** and **regenerative agriculture** movements highlight the paramount importance of community ownership and adapting practices to local socio-ecological contexts. Conversely, the **Loess Plateau** project demonstrates the efficacy of decisive state intervention and large-scale engineering for severe degradation, albeit with significant upfront investment. The **EU Soil Mission** exemplifies a data-driven, policy-incentivized approach suitable for industrialized agricultural settings.

A critical gap identified is the **lack of long-term (decadal) socio-economic and biophysical monitoring data** for most programs. While biophysical outcomes (e.g., vegetation cover) are often reported, data on sustained livelihood improvements, gender equity, and true cost-benefit analyses are less common, limiting the assessment of long-term viability.

4.3 Toward an Integrated Solution Framework:

Effective action requires moving beyond technical fixes to integrated solution frameworks. Our synthesis points to three pillars:

1. **Science-Based Practice:** Scaling up context-appropriate practices like agroforestry, cover cropping, and improved water management.
2. **Supportive Policy & Finance:** Aligning subsidies with soil-health outcomes, investing in land tenure security, and creating markets for ecosystem services (e.g., carbon credits).
3. **Inclusive Governance:** Ensuring programs are co-designed with land users, respecting local knowledge, and addressing social equity.

V. CONCLUSION

This global synthesis unequivocally establishes soil degradation as a central, multifaceted threat to food security and ecological stability. The problem is severe and widespread, but reversible. The evidence from major restoration initiatives provides a cautiously optimistic roadmap: degradation can be reversed through concerted effort.

The key insight from our analysis is that successful rehabilitation is not merely about deploying the right technology, but about **integrating science, policy, and community.** The most resilient outcomes arise from initiatives that combine biophysical restoration with socio-economic benefits for local stewards. Therefore, safeguarding global food systems requires a paradigm shift that treats soil not as an inert substrate, but as a vital, living asset. Immediate, coordinated action to scale up the integrated models highlighted in this review—supported by robust monitoring and long-term finance—is imperative to secure fertile soils and a food-secure future.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Community-Based Participatory Assessment to Inform Pollution Mitigation and a Knowledge-Attitude-Practice (KAP) Framework at Brijghat (Garh Mukteshwar), Ganga River, India

Mahesh Singh[1]; Ganesh Datt Bhat[2]; Parveen Kumar Jain[3]; Lochan Vyas[4]; Sushma Singh[5]; Ngangkham James Singh[6]; Amit Kumar Maurya[7*]

College of Agriculture Sciences, Teerthanker Mahaveer University, NH-24, Delhi Road, Moradabad - 244001, Uttar Pradesh, India

*Corresponding Author

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Abstract— *The river ghats of the Ganga basin are vital socio-ecological zones where intense religious and livelihood activities intersect with fragile riverine ecosystems. At pilgrimage sites like Brijghat (Garh Mukteshwar, Uttar Pradesh), this leads to localized pollution hotspots that degrade both ecological and cultural values. This study presents a community-based participatory assessment conducted through systematic field engagement in September 2024. It combines environmental observation, stakeholder dialogue, and an awareness campaign to diagnose key pollution sources, infrastructure gaps, and community perceptions regarding river health. Findings reveal significant accumulation of plastic and ritual waste, inadequate waste segregation facilities, and moderate levels of ecological awareness among visitors, coupled with a strong underlying willingness to engage in conservation. Critically, this pilot work directly informed the design of a structured bilingual (Hindi-English) KAP survey instrument for future quantitative research. The study concludes that academic-led, participatory diagnostics are a crucial first step in bridging national policy (Namami Gange) and local action. They build trust, generate site-specific insights, and create tailored tools for measuring and promoting behavioral change, forming a scalable, low-cost model for sustainable ghat management.*

Keywords— Brijghat, River Ganga, Solid Waste Management, Participatory Assessment, Environmental Awareness, Namami Gange, KAP Framework.

I. INTRODUCTION

Rivers are the lifeline of India's ecological, cultural, and economic systems. The Ganga River basin alone supports nearly 40% of the country's population, providing water, sustaining agriculture, fisheries, and countless livelihoods (Alley, 2008; Kumar et al., 2019). However, rapid urbanization, increasing pilgrimage tourism, ritual practices, and inadequate waste management systems have severely strained the river's assimilative capacity, negatively impacting water quality, biodiversity, and human health (Nath et al., 2023; Mishra et al., 2021). River ghats, which serve as critical socio-ecological interfaces, have become focal points for pollution accumulation due to unmanaged solid waste, ritual residues, floral offerings, and direct wastewater discharge (Dayal, 2016; Simon & Joshi, 2022).

Brijghat, located at Garh Mukteshwar, Uttar Pradesh, is a major site for religious and recreational activities on the Ganga, attracting large numbers of devotees year-round, especially during festivals and auspicious occasions (Patel et al., 2023).

Activities such as ritual bathing, idol immersion, and religious gatherings, while central to community and spiritual identity, generate substantial non-biodegradable waste, organic matter, and nutrient loads, degrading water quality, sediment health, and the aesthetic value of the riverbank (Kumar et al., 2019; Singh et al., 2017).

The Government of India's flagship Namami Gange Programme recognizes the need for an integrated approach encompassing infrastructure, regulation, and public participation (Nath et al., 2023). Evaluations suggest that technological and regulatory measures alone are insufficient without complementary behavioral change, environmental literacy, and community ownership at the local level (Singh & Sharma, 2018). In this context, Knowledge-Attitude-Practice (KAP) studies are valuable for gauging awareness, identifying perception gaps, and assessing readiness to adopt pro-environmental behaviors (Bharti et al., 2024; Kesherwani et al., 2022). However, effective KAP surveys require contextual grounding.

This study posits that a community-based participatory assessment is a vital prerequisite for designing effective, context-sensitive interventions and research tools. We conducted an academic-led field engagement at Brijghat, combining diagnostic observation, stakeholder interaction, and awareness activities. The primary objectives were to: (1) conduct a situational analysis of pollution sources and infrastructure gaps; (2) explore community perceptions and behaviors through direct dialogue; and (3) utilize these insights to develop a pilot KAP survey instrument for future quantitative research. This approach aims to bridge the policy-practice gap for the Ganga, translating national mission goals into localized, actionable strategies.

II. MATERIALS AND METHODS

2.1 Study Area:

Brijghat is situated on the right bank of the Ganga River at Garh Mukteshwar, Uttar Pradesh. As a prominent religious, cultural, and tourist node, it experiences high visitor flux, particularly during peak seasons. The area suffers from inadequate waste management infrastructure, leading to the disposal of solid waste and garbage directly on the ghat steps and banks. This makes Brijghat a representative site for studying ghat-level pollution dynamics in the Ganga basin (Nath et al., 2023).

(A)

(B)

(C)

(D)

(E)

(F)

FIGURE 1 (A, B, C, D, E, F): Ganga Champions team at Brijghat, depicting garbage accumulation, polluted fountain area, overflowing dustbins, and damaged infrastructure at the ghat

2.2 Research Design:

A qualitative, participatory research design was employed, integrating descriptive and diagnostic approaches. Field interventions were conducted on 28th and 30th September 2024, comprising a diagnostic survey visit followed by a community awareness program. This design allowed for the triangulation of data from environmental observation, stakeholder perception, and participatory engagement, enhancing the reliability of findings (Simon & Joshi, 2022; Barsay, 2022).

2.3 Data Collection Procedures:

Data was collected through three complementary activities:

1. **Systematic Environmental Observation:** Researchers conducted a visual walk-through assessment using a standardized protocol. Observations focused on: a) types and locations of waste accumulation (e.g., steps, entry points, water edge); b) condition and adequacy of waste infrastructure (bins, collection points); c) functionality of water features and other public amenities; and d) general cleanliness. Photographic documentation was used to evidence key findings (Figure 1).
2. **Structured Stakeholder Interaction:** Informal, semi-structured dialogues were held with a purposive sample of stakeholders present at the ghat. This included pilgrims (n≈15), local vendors (n≈5), residents (n≈10), and casual visitors (n≈10). Conversations, conducted in Hindi, explored: a) perceptions of pollution causes and severity; b) attribution of responsibility for cleaning; c) awareness of ecological impacts of ritual waste/plastics; and d) willingness to participate in or support mitigation measures. Key responses and emergent themes were documented in field notes.
3. **On-site Awareness Programme:** An interactive awareness session was conducted with gathered stakeholders. It focused on the ecological impact of river pollution, the importance of waste segregation, alternatives to single-use plastics, and responsible ritual practices. The engagement level and queries from participants were noted as indicators of receptivity.

2.4 Development of a Pilot KAP Instrument:

Insights from the environmental observations and stakeholder dialogues were systematically analyzed to identify key knowledge gaps, prevailing attitudes, and common practices. This analysis directly informed the design of a pilot bilingual (Hindi-English) KAP questionnaire. The instrument includes sections on demographics, knowledge of pollution sources, attitudes towards responsibility and conservation, current disposal practices, and willingness to adopt specific mitigation behaviors.

2.5 Ethical Considerations:

All interactions were voluntary, based on verbal consent. No personal identifiers were recorded. The study adhered to ethical guidelines for community-based environmental research, prioritizing respect for participants and the site's cultural significance (Barsay, 2022).

III. RESULTS

3.1 Situational Analysis: Environmental and Infrastructure Gaps:

Field observations revealed severe solid waste management challenges at Brijghat.

- **Waste Accumulation:** Prominent waste streams included plastic packaging (polythene bags, food wrappers), ritualistic materials (flower offerings, cloth pieces), and general municipal solid waste. This waste was visibly accumulated on the ghat steps, along railings, and in corners of the platform (Figure 1A, 1B).
- **Infrastructure Deficits:** Existing waste bins were insufficient in number, often in poor condition (rusted, damaged), and placed irregularly. Most observed bins were overflowing, leading to littering in surrounding areas (Figure 1D). No bins for segregated waste (wet/dry/recyclable) were present.
- **Aesthetic and Functional Decline:** Decorative water fountains in the ghat complex were non-operational and filled with stagnant, polluted water, detracting from the site's aesthetic and spiritual ambiance (Figure 1C). General maintenance of stairs and walkways was suboptimal.

Figure 1. Field observations at Brijghat, Garh Mukteshwar: (A) Accumulation of mixed waste on ghat steps; (B) Close-up of plastic and ritual waste; (C) Non-functional and polluted fountain; (D) Overflowing and damaged waste bin; (E, F) The university team conducting the awareness program and stakeholder interactions.

3.2 Stakeholder Perceptions and Behavioral Insights:

Dialogues with approximately 40 stakeholders yielded the following thematic insights:

- **Knowledge & Awareness:** A strong spiritual and emotional connection to the Ganga ("Maa Ganga") was universally expressed. However, awareness of the specific ecological harm caused by plastics and non-biodegradable ritual items was low to moderate. Most recognized "dirt" as a problem but lacked understanding of chemical contamination, biodiversity loss, or long-term sustainability issues.

- **Attitudes & Responsibility:** Pollution was frequently framed as a failure of municipal services or government authorities ("Nagarpalika should clean more often"). While acknowledging some personal responsibility, the dominant attitude placed the onus on systemic solutions. Despite this, a strong underlying reverence for the river translated into high expressed concern for its well-being.

- **Practices & Willingness to Change:** Current disposal practices were largely convenience-based, influenced by the lack of proper bins. A significant majority of respondents expressed positive receptivity to the awareness session. Many supported the idea of segregated bins, expressed interest in eco-friendly alternatives for rituals (e.g., clay idols, biodegradable flowers), and endorsed the role of educational institutions in driving change.

3.3 Output: A Context-Informed KAP Survey Instrument

The participatory process culminated in the development of a 25-item pilot KAP questionnaire. Key domains include:

- **Section A:** Socio-demographic profile.
- **Section B:** Knowledge (sources of pollution, impact of plastics, concept of river health).
- **Section C:** Attitudes (perceptions of responsibility, trust in institutions, spiritual-ecological linkage).
- **Section D:** Practices (current waste disposal, ritual material choices, participation in cleaning).
- **Section E:** Behavioral Intentions (willingness to segregate waste, use alternatives, join awareness drives).

IV. DISCUSSION

This participatory assessment underscores that effective river restoration at sacred sites like Brijghat requires initial, grounded diagnostic work to tailor broader policy frameworks to local realities. Our findings align with and contextualize existing literature on Ganga pollution (Kumar et al., 2019; Dayal, 2016). The observed gap between deep spiritual value and limited ecological knowledge confirms the need for targeted communication strategies that connect religious sentiment to environmental stewardship, a challenge noted in similar pilgrimage contexts (CPCB, 2022).

The identified infrastructure gaps—overflowing bins, no segregation—highlight a critical disconnect. While Namami Gange invests in large-scale infrastructure, localized, site-specific maintenance and provisioning at ghats remain weak. This echoes governance challenges in medium-sized pilgrimage towns along the basin (Dayal, 2016). Our study demonstrates that academic institutions can play a vital "bridging" role, conducting micro-level diagnostics and fostering dialogue, thereby operationalizing national mission goals at the grassroots level (Das & Tamminga, 2012).

The most significant outcome is the pilot KAP instrument, derived directly from community input. This addresses a common flaw in externally designed surveys that may miss local nuances. The designed tool is now primed for validation and quantitative administration to measure baselines, track changes post-intervention, and identify precise leverage points for behavior change campaigns. This model of **diagnosis-first, tool-design-second** enhances the scientific rigor and practical relevance of community-based research (Barsay, 2022).

Limitations and Future Research

This study is a qualitative, situational analysis with a modest, purposive sample. Its findings are indicative, not generalizable. The logical next step is the quantitative deployment of the developed KAP instrument to a larger, randomized sample at Brijghat and comparable ghats. Longitudinal studies are needed to assess the impact of awareness programs and infrastructure improvements on actual behavior and waste metrics.

V. CONCLUSIONS AND RECOMMENDATIONS

This community-based participatory assessment at Brijghat provides a granular understanding of pollution drivers and community dynamics, successfully informing the creation of a context-specific KAP research tool. It confirms that local communities hold a strong reverence for the Ganga and a latent willingness to act, which can be mobilized through respectful engagement and improved systems.

We recommend a multi-stakeholder action plan for Brijghat:

1. **Immediate Infrastructure:** Install and maintain clearly labeled, robust bins for waste segregation (biodegradable ritual offerings, plastics, other waste) at key inflow points on the ghat.

2. **Community-Led Initiatives:** Local administration and NGOs should promote the use of certified biodegradable materials for rituals and organize regular "ghat cleanliness drives" co-led by community groups and student volunteers.

3. **Leverage the KAP Tool:** The developed questionnaire should be used by researchers or local agencies to conduct a baseline survey, the results of which can design targeted awareness campaigns.

4. **Strengthen Institutional Partnership:** Formalize collaboration between academic institutions (like Teerthanker Mahaveer University), the local municipality, and the District Ganga Committee to enable continuous monitoring, innovation, and youth engagement.

The proposed model—participatory diagnosis leading to tailored tool development and concrete local recommendations—is scalable, low-cost, and replicable across the numerous ghats of the Ganga basin and beyond, offering a practical pathway to translate the vision of a clean Ganga into on-ground reality.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Market System Adaptation to Climate-Smart Agriculture: A Case of the Sorjan-Induced Bio-Economy in Coastal Bangladesh

Shyam Sundor Debnath[1]; S S R M Mahe Alam Sorwar[2]; Md. Golam Fazle Rabbani[3*]; Md. Anisur Rahman[4]; Sonkar Chandra Debnath[5]; Dr. Akond Mohammad Rafiul Islam[6]

[1,5]Poribar Unnayon Songstha (FDA), Bangladesh
[2,4,6]Palli Karma-Sahayak Foundation (PKSF), Bangladesh
[*3]GMark Consulting Ltd., Bangladesh
*Corresponding Author

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Abstract— *This study evaluates the transformative impact of the Climate Adaptive Sorjan Model on the agricultural market system in the coastal regions of Bangladesh, particularly in Charfasson and Lalmohan, Bhola. The research highlights how the adoption of this raised-bed and ditch farming system has catalyzed significant shifts in both backward and forward market linkages, fostering a sustainable and resilient agribusiness ecosystem. Key findings reveal a substantial expansion in the backward market for eco-friendly agricultural inputs, with bio-pesticide sales increasing by nearly 20% within a year and the number of input suppliers more than doubling in the region. This growth reflects a systemic shift toward ecological farming practices driven by farmer adoption of integrated pest management and organic fertilization. In the forward market, Sorjan-produced vegetables have achieved extensive penetration into national wholesale hubs, with over 80% of produce traded beyond local markets. The model's diversified, year-round production has attracted trader investment, ensured price premiums, and stimulated the development of a more resilient value chain. However, challenges such as post-harvest infrastructure gaps and price manipulation by middlemen persist. The study concludes that the Adaptive Sorjan Model not only enhances on-farm resilience and productivity but also actively reshapes local and regional market systems, creating a self-reinforcing cycle of demand for green inputs and premium produce. Strategic interventions in finance, market access, and supply chain development are recommended to sustain and scale this market-led climate adaptation pathway.*

Keywords— Sorjan, Climate Adaptive Agriculture, backwards and forward market, agribusiness, bio-pesticides, ecological farming.

I. INTRODUCTION

The coastal region of Bangladesh, a dynamic and fertile landscape, is paradoxically recognised as the nation's most climate-vulnerable territory. Encompassing approximately 32% of the country's land area and supporting a population of over 35 million, this region is the agrarian heartland for its inhabitants (World Bank, 2020). However, this primary livelihood source faces existential threats from a confluence of environmental and socio-economic pressures. The relentless intrusion of salinity, driven by sea-level rise and reduced freshwater flow in the dry season, is progressively rendering vast tracts of land unsuitable for conventional agriculture (Habib et al., 2022). This slow-onset disaster is compounded by acute shocks—frequent and intense cyclones, tidal surges, and seasonal flooding—that lead to catastrophic waterlogging, destroying standing crops and eroding precious topsoil (IPCC, 2022).

These climate-induced challenges are severely exacerbated by a critical lack of fresh irrigation water during the dry months, forcing farmers into periods of fallow land or low-yield monocropping. The result is a narrowing of cropping diversity and a direct threat to regional food security and economic stability (MoA, 2021). There is, therefore, an urgent need to identify, validate, and scale adaptive agricultural practices that can withstand these shocks, ensuring the future of coastal communities.

In response to these challenges, the Sorjan farming system has re-emerged as a beacon of climate-smart agriculture. While its principles are rooted in ancient practices, its modern application represents a paradigm shift. Sorjan is a meticulously designed raised-bed and ditch system featuring alternating deep channels (sinks) and high, wide beds (ridges). This design fosters a dynamic and resilient micro-ecosystem that provides multifaceted benefits, including proactive salinity management, improved drainage, integrated water reservoirs, and opportunities for crop and fish diversification (BARI, 2019). As such, the Sorjan system signifies a transition from conventional farming that is vulnerable to environmental challenges toward a more productive, diversified, and ecologically balanced approach.

While much of the existing research has focused on the agronomic and environmental benefits of Sorjan farming, a significant gap remains in understanding how its adoption influences and transforms local and regional agricultural market systems. The success of climate-adaptive technologies depends not only on on-farm adoption but also on the responsiveness of input supply chains, output market linkages, and value chain actors. Therefore, this study shifts the analytical lens from a purely comparative farm-level assessment to a systemic examination of market adaptation spurred by the Climate Adaptive Sorjan Model. the research aims to:

- Assess the influence of the Climate Adaptive Sorjan Model on the transformation of the agricultural input market, specifically examining the growth and diversification of eco-friendly input supply chains in coastal Bangladesh.
- Evaluate the changes in forward market linkages resulting from Sorjan-based production, including market penetration, price dynamics, and trader engagement in the value chain.
- Identify the key drivers and barriers in the adoption of market-supporting mechanisms that enable scaling of climate-resilient farming systems in vulnerable coastal regions.
- Propose strategic recommendations for strengthening market systems that support the widespread replication and scalability of climate-adaptive agricultural models beyond project-based interventions.

II. LITERATURE REVIEW

Bangladesh's coastal belt is on the frontline of the global climate crisis. Scholarly work consistently highlights the severe climatic stress this region endures. Rising sea levels are causing saline water to intrude ever deeper into freshwater aquifers and river systems, a phenomenon extensively documented by Clarke et al. (2018). This salinity intrusion is identified as a primary constraint to crop production, negatively affecting soil health and plant growth (Sarwar, 2021). Furthermore, the increased frequency and intensity of cyclones and associated tidal surges not only cause immediate crop loss but also lead to prolonged waterlogging, which exacerbates salinity and destroys soil structure (Dasgupta et al., 2015). These factors collectively render traditional farming methods increasingly ineffective, leading to reduced crop yields, loss of livelihoods, and heightened food insecurity.

Sorjan farming, with its origins in Indonesia, has been identified as a transformative agricultural technique for Bangladesh's coastal regions. The system's core design involves constructing raised beds (typically 1–3 meters wide and 60–90 cm high) with adjacent water channels. As described by Uddin et al. (2020), these channels serve a dual purpose: storing vital irrigation water during dry seasons and supporting productive fish farming during wet months. The elevated beds are strategically designed to rise above normal flood levels, thereby mitigating waterlogging and reducing salinity stress on plant root zones. Research shows several innovative variants of this method have been developed:

- Pit cropping utilizes organic-filled jute bags placed in saline soils, creating isolated pockets of fertility (Hossain et al., 2021).
- Trellising systems are integrated for vine crops like gourds and beans, maximizing vertical space and light interception (Bala, 2022).
- Integrated systems combine vegetables, fruits, and fish, creating a synergistic agro-ecosystem that enhances resource use efficiency (Kabir et al., 2020).

Empirical studies demonstrate that Sorjan farming enables significant benefits. It facilitates year-round production of high-value vegetables and fish, even in areas previously deemed uncultivable due to waterlogging or salinity (Uddin et al., 2020). This is achieved through crop diversification, where farmers can cultivate a wide range of species, including leafy greens, gourds, tomatoes, eggplants, and fruit trees such as bananas and papayas (Hossain et al., 2021). The economic impact is substantial. Research by the International Food Policy Research Institute (IFPRI, 2022) indicates that well-managed Sorjan systems can generate net returns of BDT 200,000–250,000 per hectare from the second year onwards. This directly translates to enhanced household income, food security, and nutrition, particularly for marginal and landless farmers (Bala, 2022).

Beyond economics, Sorjan farming makes a profound contribution to environmental sustainability and social equity. It builds climate resilience by physically protecting crops from flood damage and diluting salt concentration in the root zone (Kabir et al., 2020). The system also promotes carbon sequestration through increased biomass production and the incorporation of organic matter into the soil (Zaman et al., 2022). Practices such as leguminous crop rotation and mulching, integral to the system, lead to significant improvements in soil health over time (Hossain et al., 2021). From a social perspective, the system's accessible, low-input nature has been shown to empower women and smallholders, providing them with a reliable and dignified source of livelihood (Uddin et al., 2020

While the existing body of research robustly establishes the agronomic viability, economic benefit, and ecological promise of the Sorjan system, significant gaps remain regarding its systemic market impacts. Most studies focus on farm-level productivity, income comparisons, or environmental outcomes (e.g., Uddin et al., 2020; IFPRI, 2022), with limited investigation into how the adoption of such climate-smart practices reshapes local and regional agricultural market structures.

This study addresses these gaps by shifting the analytical focus from a purely comparative farm-level assessment to a holistic examination of market system adaptation. It investigates how the Climate Adaptive Sorjan Model catalyzes change in both backward linkages (input supply chains for eco-friendly products) and forward linkages (output markets and trade networks). By doing so, it contributes to the broader discourse on scaling climate-resilient agriculture, emphasizing that technological adoption must be supported by responsive and resilient market ecosystems to achieve sustainable transformation.

III. MATERIAL AND METHODS

This study employed a **mixed-methods case study design** to investigate the adaptation of agricultural market systems in response to the widespread adoption of the Climate Adaptive Sorjan Model in coastal Bangladesh. The research was conducted as a holistic, single-case study of the Bhola district, a region characterized by high climate vulnerability and significant promotion of the Sorjan system. This design was chosen to enable an in-depth, contextual exploration of the complex interactions between a climate-resilient farming practice and its surrounding economic ecosystem, focusing on both backward (input) and forward (output) market linkages. The mixed-methods approach allowed for the triangulation of qualitative insights on market processes and actor behaviours with quantitative data on market trends, providing a comprehensive understanding of systemic change.

3.1 Study Area:

The study was conducted in Bhola district, specifically in the coastal upazilas of **Charfasson and Lalmohan**. This site was selected due to its representative vulnerability to salinity, waterlogging, and cyclonic events, and because it has been a focal area for promoting the Climate Adaptive Sorjan Model under the Rural Microenterprise Transformation Project (RMTP). The concentration of adopters in this region provided a unique opportunity to observe emerging market dynamics around a specific agricultural innovation. Data were collected in October 2025 from four primary sources to ensure methodological triangulation and data validity.

3.2 Data Collection Procedures:

3.2.1 In-Depth Interviews (IDIs):

Semi-structured interviews were conducted with 37 farmers to understand on-farm decision-making, input sourcing, and market engagement practices. The sample included farmers practicing the Adaptive Sorjan Model to capture the producer perspective driving market demand. The interview guide was designed to explore changes in input procurement (e.g., shift to bio-pesticides), selling strategies, relationships with traders, and perceptions of market access and fairness.

3.2.2 Key Informant Interviews (KIIs):

A total of 12 KIIs were conducted with actors across the agricultural value chain to capture systemic perspectives. Participants were purposively selected and included 5 representatives from major companies (e.g., Ispahani) and local agro-inputs retailers to discuss changes in product demand, sales trends, and supply chain expansion. 4 local buyers (*Baparis)* and regional wholesalers involved in procuring and distributing Sorjan produce to understand changes in sourcing, pricing, quality demands, and their evolving role in the value chain and 3 Institutional Actors from the Department of Agricultural Extension (DAE) and project implementing staff (FDA/PKSF) to gather insights on programmatic support and observed market shifts.

3.2.3 Focus Group Discussions (FGDs):

Three separate FGDs were held, each with 8-10 participants, to explore shared community experiences and collective challenges related to the market system. Two FGDs were with Sorjan-adopting farmers, and one was with a mixed group of conventional and transitioning farmers. Discussions focused on themes of collective bargaining, price transparency, access to finance, and perceived power dynamics with middlemen.

3.2.4 Secondary and Quantitative Market Data:

To objectively measure market growth and trends, secondary sales data for the period 2022–2025 were obtained from a leading national agri-input company (Ispahani) operating in Bhola. This dataset included from the annual and quarterly sales revenue for bio-pesticides, chemical pesticides, and seeds, volume sales data for specific bio-inputs (e.g., pheromone traps) and records of distributor network expansion within the district. These data provided a reliable, third-party validation of market transformations described qualitatively by participants.

TABLE 1
DATA COLLECTION SUMMARY

Method	Target Respondents	Sample Size	Primary Purpose
In-Depth Interviews (IDIs)	Farmers (Sorjan adopters)	37	Understand producer-level market interactions, input use, and sales strategies.
Key Informant Interviews (KIIs)	Input Suppliers, Traders, DAE/Project Officials	12	Analyze systemic changes in supply chains, trade networks, and institutional roles.
Focus Group Discussions (FGDs)	Farmer groups	3 (8-10 each)	Explore community perceptions, collective challenges, and market dynamics.
Secondary Data Analysis	Company sales records, project reports	N/A	Quantify market growth trends and validate qualitative findings.

3.3 Data Analysis:

3.3.1 Qualitative Data Analysis:

All interviews and FGDs were audio-recorded, transcribed, and translated into English. The transcripts were analyzed using thematic analysis. An initial codebook was developed based on research objectives, focusing on themes such as "input market evolution," "trader-farmer relationships," "price mechanisms," "financial access," and "institutional support." Codes were applied iteratively, and emerging themes were refined to construct a coherent narrative of the market adaptation system.

3.3.2 Quantitative Market Data Analysis:

Secondary sales data were cleaned and analyzed using descriptive statistics. Trend analysis was performed to calculate year-on-year growth rates for bio-pesticide sales. Sales distribution across different dealer locations was mapped to identify geographic hubs of market activity linked to Sorjan adoption. This quantitative analysis provided empirical evidence of market scaling and product diversification.

3.4 Limitations:

While the chosen methodology provides valuable insights, several limitations should be acknowledged. The findings are context-specific to Bhola district. While they offer deep insight into market adaptation processes, direct extrapolation to other regions with differing agro-ecological, infrastructural, or market conditions should be made cautiously. Additionally, the study captures a snapshot of market dynamics at a particular point in the adoption curve. Longitudinal data would be required to fully understand the sustainability of observed market changes and long-term systemic shifts. Moreover, sales data from a major input provider are indicative of broader trends, they do not capture the entire market, including sales from smaller local suppliers or informal input exchanges, potentially underrepresenting total market activity.

IV. RESULT AND DISCUSSION

The empirical findings of the study, structured to first establish the nature and scale of the transformative agricultural practice climate adaptive Sorjan model and then analyze the resultant systemic market adaptations. The data illustrate a clear causal pathway, i.e. a shift to a knowledge-intensive, ecological farming system creates new patterns of input demand and output supply, where local and regional markets are dynamically responding. Field data reveal that the promoted Sorjan system is not merely a water management technique but a sophisticated, integrated agro-enterprise. Its adoption signifies a fundamental departure from conventional coastal agriculture.

4.1 Core Structural and Management Shifts:

The system is based on constructing wide, elevated beds (Sorjan) adjacent to integrated water channels or ponds. This infrastructure enables synergistic agro-aquaculture, with 57% of adopting farmers cultivating fish like Tilapia and Rui in the ditches. This integration is pivotal, providing secondary income (BDT 40,000–60,000 annually per farmer), on-farm protein, and nutrient-rich irrigation water, reducing chemical fertilizer dependency by over two-thirds.

4.2 Knowledge-Intensive Cropping and Ecological Management:

The most significant departure from convention is the shift to complex, multi-tiered cropping. Farmers cultivate up to four crops simultaneously on the same bed (e.g., Cucumber, Mud Potato, Chilli, and Bitter Gourd), ensuring continuous harvest and income. This diversity is managed through ecological practices that form the core of the model's input profile:

- A shift to balanced, knowledge-based strategies. Farmers heavily use vermicompost and other organic fertilizers, guided by soil testing. Chemical fertilizer (Urea, TSP, MOP) use has been reduced to one-third or less of previous levels.
- Widespread adoption of Integrated Pest Management (IPM) has drastically altered input demand. Farmers now rely on Bio-pesticides (derived from Neem, Akand), Physical traps (pheromone traps, yellow sticky traps) and Repellent/companion crops (Marigold, Tulsi/Basil) planted as borders. As a result, pesticide spraying frequency has fallen from 10-15 to just 4 times per season for cucumber.
- Practices like using Elephant apple (Chalta) as a natural zinc supplement demonstrate farmer-led adaptation within the ecological framework.

4.3 Socio-Economic Driver:

The system's appeal is underscored by strong socio-economic indicators. 49% (18 of 37) of engaged farmers are aged 18-35, indicating the success of attracting young people to agriculture. The economic rationale is clear. A comparative financial analysis for a local standard 160-decimal plot shows that while the ecological Sorjan system incurs a 9% higher operational cost (largely due to multi-crop seeds and initial IPM infrastructure), it generates a 22% higher net profit (BDT 447,450 vs. BDT 366,600) than a conventional mono-cropping system on the same area of land. This profitability, driven by diversified output (including fish and high-value relay crops like Chilli), is the primary engine for adoption and expansion, with 96% of adopters planning to scale their operations.

4.4 Transformation of the Backwards Market:

The adoption of the ecological Sorjan system has fundamentally reshaped demand and supply structures for agricultural inputs, catalyzing a shift from chemical-intensive to biology-intensive farming.

4.4.1 Market Growth for Eco-Friendly Inputs:

Sales data from a leading national agri-input company (Ispahani) provide certain evidence of a rapidly expanding market for bio-pesticides and Integrated.Pest Management (IPM) products in Bhola district. Revenue from bio-pesticides grew from BDT 61 lakh in 2023 to BDT 73 lakh in 2024, a nearly 20% year-on-year increase. The accelerated adoption is further underscored by sales of BDT 26 lakh in just the first three months of 2025. High-volume sales of specific inputs, such as 35,000 pheromone trap pieces in 2024, indicate widespread, practical application. Assuming a standard recommendation of 2 traps per 6 decimals of land, these sales alone serviced a substantial cultivated area, directly linked to Sorjan adoption clusters.

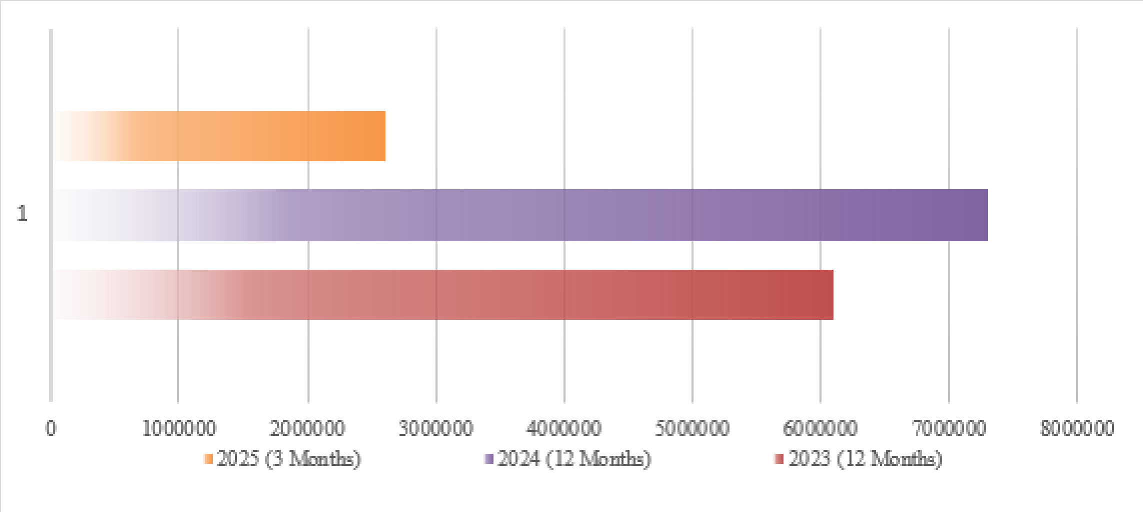

FIGURE 1: Annual Growth in Bio-pesticide Sales Revenue in Bhola District (2023-2025 Projection)

4.4.2 Supply Chain Expansion:

In response to this rising demand, the input supply chain has undergone a structural transformation. The number of Ispahani distributors in Bhola is now more than doubled, from 5 in 2022 to 11 at present. Notably, two dealers in Charfassion alone account for 40-45% of the district's total bio-input sales, confirming that Sorjan farming hubs have become epicenters of demand and are strategically shaping corporate distribution networks. The market has also matured beyond basic products, with a diversified portfolio now available, such as Bio-Chomok for fruit borers and K-mite for mites, indicating a sophisticated and responsive supply side aligned with the complex pest management needs of diversified Sorjan systems.

4.4.3 Farmer Motivations and Behavioural Shift:

Qualitative data from farmers interprets the drivers behind this market shift, as reducing the use of chemical pesticides and increasing the use of pheromone traps and bio-pesticides enables farmers to cultivate fish in the ditch. In FGDs, farmers reported reducing chemical pesticide sprays from 10-15 times per season to just 2-4 times for key crops, such as cucumber, primarily substituting them with bio alternatives.

4.5 Evolution of Forward Market Linkages:

The consistent, diversified, and quality-enhanced production from Sorjan systems has precipitated a significant reconfiguration of output market linkages. Sorjan produce has successfully breached local consumption boundaries. Over 80% of surveyed farmers' marketable surplus is now traded beyond the local Bhola markets. The produce has penetrated major national wholesale hubs, with Dhaka's Kawran Bazar and Shyam Bazar absorbing approximately 40% of the total trade, followed by Noakhali (24%) and Chattogram (16%). This geographic expansion demonstrates the model's scalability and the strong, consistent demand for its output in competitive urban markets.

4.5.1 Investment in the Value Chain:

Recognising the value of a reliable, high-quality supply of vegetables, traders have actively adapted their roles, such as advance payments to trusted Sorjan farmers for input purchases and securing their quality vegetable supply. Some traders offer support in the form of renting irrigation pumps or power tillers. Besides, superior shelf life, the appearance of Sorjan vegetables allows them to command a price premium of 2-5% over conventional produce.

This discussion synthesizes the key findings to extract broader lessons on market-led climate adaptation, identifies persistent challenges that threaten the sustainability and equity of the Sorjan model's expansion, and highlights actionable opportunities. The transformation observed in Bhola offers several critical insights for scaling climate-resilient agriculture are as follows:

- The success of the Sorjan system lies not only in its agronomic resilience but in its inherent compatibility with market demand. Its multi-cropping pattern produces a year-round mix of high-value vegetables that align with trader needs, while its ecological practices produce quality. This demonstrates that for an adaptive technology to scale, its output must be commercially viable and its input requirements must be sustainably supplied.
- The study provides a clear case of agricultural innovation driving parallel market innovation. Farmer adoption of IPM did not occur in a vacuum; it created a profitable demand for bio-inputs, which commercial suppliers rapidly met by expanding distribution networks and diversifying products. This virtuous cycle between adoption and market responsiveness is a crucial replicability factor.

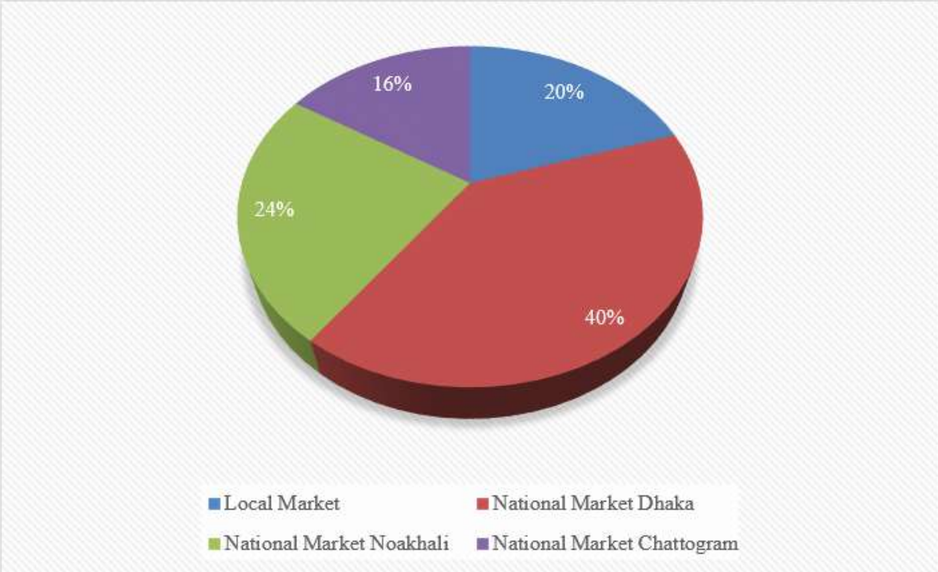

FIGURE 2. Market Destinations for Sorjan-Produced Vegetables

Despite the promising adaptation, the study uncovers deep-seated market failures that risk concentrating benefits and stifling inclusive growth. The most reported constraint was the collusion among middlemen (*Baparis*) to depress farm-gate prices, especially for perishable produce. Without mechanisms for price transparency or collective bargaining, the model's economic benefits are significantly diluted at the producer level. Moreover, the growth of the bio-input market is geographically uneven and concentrated under limited competitive pressure. While a major supplier like Ispahani has successfully expanded its network, its dominant market share in key Sorjan hubs raises concerns about long-term price competitiveness and farmer choice. Furthermore, production innovation has outpaced the development of market infrastructure. The drastic price collapse for overproduction, such as country bean seeds falling from BDT 120/kg to BDT 40/kg within weeks, is directly attributable to a lack of cold storage and processing facilities.

Addressing these challenges requires moving beyond promoting the farming technique alone to actively shaping an enabling market environment. Agribusiness companies can develop a last-mile distribution network for remote *chars*, potentially using mobile vendors. Public extension services could supplement this by validating and promoting low-cost, local bio-inputs (e.g., Neem extract preparation) to reduce dependency on commercial channels and mitigate the power of syndicates. In addition, developing tailored financial products with MFIs and banks for Sorjan establishment *and* post-harvest infrastructure. This could include loans for shared cold storage facilities or community-based processing units.

V. CONCLUSION

This study confirms that the Climate Adaptive Sorjan Model has catalyzed significant market system transformation in coastal Bangladesh. The shift to this ecological farming system has spurred rapid growth in the bio-input market and strengthened forward market linkages, integrating Sorjan produce into national supply chains. However, scaling remains constrained by persistent market imperfections, including price manipulation by middlemen, limited competitiveness in input markets, and a critical lack of post-harvest infrastructure. For the model to realize its full potential, strategic interventions must address these structural barriers by fostering more inclusive and competitive market institutions. Ultimately, the Sorjan experience demonstrates that sustainable climate adaptation requires not only technological adoption but also the development of equitable and resilient market ecosystems that enable farmers to thrive amid environmental change.

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CONFLICT OF INTEREST

The authors declare no direct conflict of interest regarding the publication of this study. The research was conducted independently by **GMark Consulting Ltd.** under the sponsorship of **Palli Karma-Sahayak Foundation (PKSF)** with funding from **IFAD** and **DANIDA**. The findings and conclusions presented in this report are based solely on empirical data and do not reflect the commercial interests of any supporting or implementing organization. The authors affirm that there are no financial or personal relationships that could be perceived as influencing the research outcomes or the reporting of results.

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