Review Article

Review on Potential of Poplar (*Populus deltoides*) Based Agroforestry for Economic Benefits and Climate Change Mitigation

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Abstract | The world is experiencing increased levels of atmospheric carbon dioxide, increasing temperatures, precipitation fluctuation patterns, and other climate change impacts due to increased fossil fuel consumption which affects community activities. Poplar (*Populus deltoides*) is a fast-growing tree species that grows extensively on farmlands in order to fulfill socioeconomic needs as well as climate mitigation and adaptation. The current study reviewed the social, economic and environmental significance of Eastern Cottonwood based agroforestry system. The current economic review of *Populus deltoides* shows that average net return and average net present value are 11121USD ha^{-1}, INR. 793,579 ha^{-1} with benefit cost ratio of 2.45. The land expectation value and internal rate of return were found 9570USD ha^{-1} and 11121USD ha^{-1}, with an internal rate of return 52 % ha^{-1}. The review concluded that the potential of poplar (*Populus deltoides*) based agroforestry system can be utilized by overcoming financial, technical, and institutional barriers for planned adaptation.

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Introduction

Poplar (*Populus deltoides*), commonly referred to as eastern cottonwood or eastern poplar, is famed for its production of fluffy seeds that bear a resemblance to snow when they descend to the ground. In Azad Jammu and Kashmir, this tree species is also known by various names, including Eastern Cottonwood, Plains Cottonwood, Rio Grande Cottonwood, and Plains Poplar Rousee Poplar (AJK) according to (Krishnakumar *et al*., 2011). The term poplar (*Populus deltoides*) originates from the Greek word delta, which pertains to three-sided figures like triangles or deltas (www.nzpcn.org.nz).

The poplar (*Populus deltoides*) tree is medium to large in size, reaching heights of 20-30 meters (maximum 50 m), with a diameter at breast height of 100 cm. Its bark has a grayish-green color and smooth texture, transitioning to a blackish hue with furrows as it matures. The trunk appears short and sturdy in open spaces, frequently splitting into several broad, widely spreading limbs close to the ground. This gives rise to a broad, unevenly shaped open crown, as described previously according to (Orwa *et al*., 2009).

Poplar (*Populus deltoides*) is a renowned agroforestry species originating in North America. It has significant economic value in the agroforestry sector according to (Singh, 2016). Recognized as eastern cottonwood (*Populus deltoides Bartr*.), this rapidly growing tree is a prime contender for short-rotation cultivation for biofuel production. Its cultivation spans Asia, Europe, and North America according to (Dipesh *et al*., 2017). In various developing nations, it has been introduced and nurtured as an agroforestry resource, coexisting with agricultural crops and adapting to local climate conditions over time (Sheikh, 1993).

Materials and Methods

A comprehensive literature search was initiated with help of electronic databases, including Science Direct (https://www.sciencedirect.com), Scopus (https://www.scopus.com/home.uri) and Google Scholar (https://scholar.google.com/), Research Gate (https://www.researchgate.net/) and Sci hub and Digitala Vetenskapliga Arkivet (https://www.diva-portal.org/) Additionally, we collected further records from review articles and research articles that met our initial eligibility criteria. The search was performed using a combination of keywords i.e., *Populus deltoides*, productivity, net return value, benefit: cost ratio, biomass and carbon sequestration. The search was limited to articles published between 1993 and 2023. The review paper comprises of (1) Introduction, (2) Review Methodology, (3) Economic returns, (4) Climate change mitigation and (5) Challenges in Poplar based agroforestry system.

The methodological quality assessment was done by economic benefit factors such as net return value, benefit cost ration, land expectation value, plantation spacing. While the climate mitigation parameters were biomass per hectare, carbon stock per hectare.

Productivity of poplar (Populus deltoides)

Poplar (*Populus deltoides*) was found at altitudes of up to 1000 m, where the typical yearly temperature varies from 8 to 14°C, and the average annual precipitation ranges from 600 to 1500 mm. While *P. deltoids* can survive on unproductive sandy soils, sandy loams, and somewhat compact clays, it thrives in damp, adequately drained, fine, sandy loams, or silts located close to streams, with a pH level spanning from 4.5 to 8 according to (Orwa *et al*., 2009).

Poplar (*Populus deltoides*) has the potential to reproduce naturally and artificially through regeneration. However, natural regeneration is infrequent from seeds, except in specific conditions such as landslides, recently thawed soil, and waterways. Cottonwood plantations cultivate in tropical and subtropical regions, which are also considered favorable for cultivating various other agricultural products such as sugarcane, wheat, potatoes, mustard, corn, legumes, vegetables, forage crops, and medicinal plants according to (Kumar and Yadav, 2022a).

The primary determinant of productivity in any vegetation system is the ability of its various components to generate biomass and store carbon influenced by factors such as the type and age of plants, as well as environmental elements like climate, soil properties, terrain, and other living organisms according to (Chaturvedi *et al*., 2016). Depending on a company's scale, gains ranging from 38.8% to 100.90% of initial investments have been documented within a year through the cultivation of nursery plants according to (Anita and Anubha, 2020). Poplar (*Populus deltoides*) exhibits rapid growth, with Mean Annual Increment (MAI) of 20-25 m^3/ha/yr in block and boundary plantations in farmers' fields. The reported yield is 1.125 million m^3/yr, with a range of 20-40 m^3/ha/yr in Pakistan according to (Sheikh, 1993).

In Pakistan, at a rotation age of 8-12 years, the trees produce an average annual yield of 10-30 m^3/ha, while in India, a study according to (Krishnakumar *et al*., 2010) records an annual yield of 46.92 m^3/ha. Poplars are characterized by their rapid growth, achieving a height of around 25 m and a diameter at breast height (DBH) of 30 cm within 6 to 8 years. The average MAI for poplar plantations varies from 20 to 25 m^3/ha/year according to (Anita and Anubha, 2020).

Economic returns- poplar (Populus deltoides) based agroforestry system

Poplar based agroforestry practices encompass an approximate land area of 1 billion hectares and engage over 1.2 billion individuals globally according to (Ghale *et al*., 2022). Agroforestry involving poplar trees and flowering annuals presents significant prospects for enhancing agricultural variety and achieving greater yields in comparison to conventional crops grown in open fields or beneath poplar tree cover, as indicated by the findings according to (Rani *et al*., 2011). Poplar (*Populus deltoides*) is renowned for its rapid growth, vegetative reproduction, and soil enhancement capabilities. This tree variety not only provides an extra income source for farmers but also yields valuable raw materials used in the production of diverse items such as plywood, paper pulp, furniture, fiberboard, veneer, spors equipment, newsprint, high-quality paper, packaging material, and match splints, as according to (Singh and Lodhiyal, 2009). Apart from supplying ecosystem services and mitigating human impacts on natural forests, agroforestry generates benefits and revenue through carbon capture, wood-based energy, increased soil fertility, and the amelioration of local climatic conditions, as outlined in the study by (Mbow *et al*., 2014). The sorghum-berseem based poplar planation of 10 × 2 m spacing at rotation of 12 years shows the highest net returns of INR. 1,191,241 ha^{-1}, NPV at rate of 12% discounting 409,673 ha^{-1}), Benefit cost ratio was found 1: 2.22, IRR (70%), while highest land equivalent ratio (2.28) and land expectation value (INR 2, 242, 372 ha^{-1} according to (Chavan and Dhillon, 2019).

The optimal rotation ages were 10 and 8 years for 3m × 3m and 3m × 4m density, respectively in case economic value of timber. Optimal rotation ages in case of carbon sequestration along with timber value was increased to 14 and 11 years for the same two densities, respectively (Abedi *et al*., 2022).

Table 1 shows the cost and income analysis from intercrop as well as poplar plantation indicated that B-C ratio was 2.87, internal rate of return was 57.50 % and net present worth was USD 14772 Ha^{-1} (Harinder and Murthy, 2016). For one year old entire transplants (ETPs) of poplar, the costs incurred were US$ 4.82 per tree for 8 years including labour, irrigation, fertilizers, pesticides and fungicides, technical advice, insurance premium etc. (Jain and Singh, 2000).

The average net return is 1,026,055 at rotation age of 7 years for one hectare of planation. The net present value (NPV) of poplar plantation for an area of one hectare is 353,688 at rotation of 7 year and 9 per cent discount rate and the net discounted return. The calculated benefit-cost ratio of 1:2.44 was found at this discount rate of interest The overall internal rate of return was found 39.06 % ha^{-1} of poplar planation which proved that Poplar plantation is economically viable (Pankaj *et al*., 2016). The undiscounted returns depend upon the age of poplar while using net discounting criteria, the returns are highest at the age of 4th year if cost of capital is 15 % and above in case of agro-forestry systems AFS-I (wheat + kharif fodder for the 1st four years) and AFS-II (sugarcane for first two years and wheat during 3–4 years) of poplar plantation according to (Singh and Kaur, 2020).

Agroforestry is economically viable at the discount rate of 10% over 8 years rotation using Net present worth and benefit: cost ratio. The internal rate of return is more than 36 % at 8 years of rotation age according to (Sharma *et al*., 2020). While considering its economic value of carbon sequestration, 27 years are its optimal rotation age according to (Abedi *et al*., 2023) as shown in Table 1.

Agroforestry practices involving Poplar (*Populus deltoides*) trees offer valuable mitigation and adaptation strategies for enhancing food security, particularly for small-scale farmers. This underscores the critical importance of prioritizing Agroforestry on a global scale due to its manifold socio-environmental

Table 1: *Economic benefits of poplar based agroforestry system.*

S. No	NR/ha	NPV (INR /ha)	B:C	IRR (%/ha)	LER	LEV	Age	Spacing (m)	Agroforestry system	Source
1	549,367	222951	1: 1.65	85		1220337	8	15 × 9	Sorghum-wheat	(Chavan *et al*., 2022)
2	1,191,241	409,673	1: 2.22	70	2.28	2,242,372	12	10 × 2	Sorghum-berseem	(Chavan and Dhillon, 2019)
3	1,026,055	353,688	1; 2.44	39.06	-		7	-	Sole land	(Pankaj *et al*., 2016)
4	-	1,228,162	1: 2.87	57.5	-	-	8	6 × 1.5	Raprian wetland	(Harider and Mavi, 2016)
5	-	1,284,000	1: 2.94	40.55	-	-	10	3 × 4	Sorghum berseem trifolium	(Himshikha *et al*., 2018)
6	-	1,263,000	1:2.62	22.43	-	-	9	-	Sorghum-trifolium	

NR= Net Returns, NPV= Net Present Value, B:C= Benefit Coat ratio, IRR= Internal Rate of Return, LER= Land Expectation Return,

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LEV= Land Expectation Value, USD= US Dollars

advantages. The Land Equivalent Ratio (LER) values demonstrated that agroforestry systems outperformed monocultures by 36–100%, with LER ranging from 1.36 to 2.00. A comparison between Denmark and the United Kingdom revealed that the agroforestry gross margin was higher in the UK (€5083 ha/year) compared to Denmark (€112 ha/year). Moreover, the agricultural component generated greater profits than the tree component, leading to an adverse impact according to (Lehmann *et al*., 2020).

Table 2: *Biomass and carbon table of Popoulus deltoides (Poplar) growing on farmlands.*

DBH (cm)	Height (m)	Dry biomass (t)	Carbon (t)	DBH (cm)	Height (m)	Dry Biomass (t)	Carbon (t)
6	8.13	0.005	0.002	54	26.59	1.019	0.479
8	10.55	0.010	0.005	56	26.89	1.105	0.519
10	12.42	0.019	0.009	58	27.19	1.195	0.562
12	13.95	0.030	0.014	60	27.47	1.289	0.606
14	15.25	0.044	0.021	62	27.75	1.386	0.652
16	16.37	0.061	0.029	64	28.02	1.488	0.699
18	17.36	0.081	0.038	66	28.27	1.593	0.748
20	18.25	0.104	0.049	68	28.53	1.702	0.800
22	19.05	0.130	0.061	70	28.77	1.815	0.853
24	19.78	0.160	0.075	72	29.01	1.931	0.908
26	20.45	0.193	0.091	74	29.24	2.052	0.964
28	21.07	0.229	0.108	76	29.46	2.176	1.023
30	21.67	0.269	0.126	78	29.68	2.304	1.083
32	22.19	0.312	0.146	80	29.89	2.436	1.145
34	22.7	0.358	0.168	82	30.1	2.573	1.209
36	23.18	0.408	0.192	84	30.3	2.713	1.275
38	23.64	0.461	0.217	86	30.5	2.857	1.343
40	24.07	0.518	0.244	88	30.69	3.004	1.412
42	24.48	0.579	0.272	90	30.88	3.156	1.483
44	24.87	0.643	0.302	92	31.07	3.313	1.557
46	25.24	0.711	0.334	94	31.25	3.473	1.632
48	25.6	0.782	0.368	96	31.42	3.636	1.709
50	25.94	0.857	0.403	98	31.6	3.804	1.788
52	26.27	0.936	0.440	100	31.77	3.976	1.869

Source: *(Ali, 2020). Derived from developed biomass model M= 0.0194 (D2H)0.9654. H= -6.9198+8.4004lnD. Where M is the dry biomass in Kg, D is DBH in cm, H is the height in m and ln is the natural log.*

In order to protect the extensive cottonwood forests that exist on the natural floodplain of unaltered sections of the Missouri River in the United States, either to counteract potential future losses due to natural aging and ecological progression, it is essential for such tree planting efforts to be conducted consistently and on a large scale according to (Dixon *et al*., 2012). Economic analysis of Poplar (*Populus deltoides*) revealed that a poplar plantation established along an east-west boundary exhibited the highest net profits at $6,639 per hectare, the lowest net present value at $2,694 per hectare, and the highest LEV at $14,748 per hectare according to (Chavan *et al*., 2022) Poplar (*Populus deltoides*) wood obtained from a farm was typically sold for $44.0 USD, while subsistence, economically-oriented, and above-economic farms generated revenues of $20.5, $20.5, and $95 per unit, respectively. The significant correlation between globalization and agroforestry lies in the fact that 65% of non-agroforestry farmers were categorized as medium cosmopolites according to (Singh and Lodhiyal, 2009).

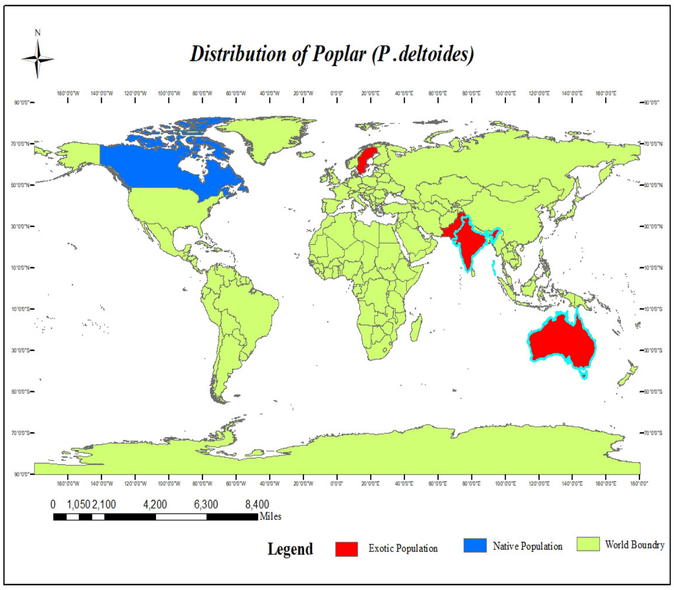

Figure 1: *Map of geographical distribution of Poplar.* **Source:** *(Orwa et al., 2009).*

Figure 2: *Single tree sale rate.*

Source: *(Usman et al., 2022).*

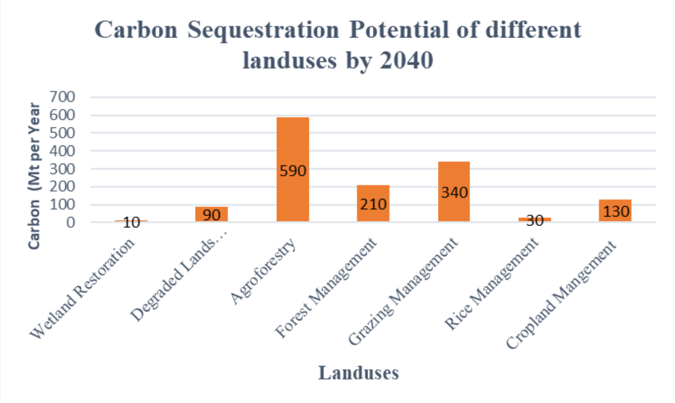

Figure 3: *Carbon sequestration potential of different land use systems by 2040 (adapted from IPCC, 2000).* **Source:** *(Jose and Bardhan, 2012).*

The predominant sales in Pakistan involve the trade of a single *Populus deltoides* tree, characterized by a 10-inch diameter and 20-foot height, fetching prices exceeding PKR. 850/- according to (Usman *et al.*, 2022). The net present value was ranged from 1105.54 € ha^{-1} (Baseline) to 9620.30 € ha^{-1} (Optimum) after 12 years with 4 rotations of 3 years as result of coppice silvicultural system. Land rent (31.88 %), irrigation (16.61 %), and cut-and-chip harvesting (11.87 %) are most critical cost factors according to (Fuertes *et al.*, 2021).

The current economic review of the *Populus deltoides* showed that average net return and average net present value are INR. 922,221 ha^{-1}, INR. 793,579 ha^{-1} with B:C of 2.45, respectively. The land expectation value, and land internal rate of return were found INR. 922,221 ha^{-1} and INR. 793,579 ha-with internal rate of return 52 % ha^{-1}.

Climate change mitigative significance

In pursuit of net-zero emissions targets, nations and corporations are contemplating strategies to counterbalance remaining greenhouse gas emissions according to (COP 26, 2021). Employing carbon capture techniques, agroforestry plays a crucial role in diminishing greenhouse gas emissions compared to atmospheric carbon dioxide levels according to (Rizvi *et al.*, 2019). The practice of agroforestry has gained increased prominence as a means of carbon storage (C) and addressing global climate change, especially since the Kyoto Protocol according to (Murthy, 2013). Agroforestry systems offer substantial opportunities to integrate both adaptation and mitigation measures, enhancing the system's resilience against the adverse effects of climate change according to (Jose and Bardhan, 2012).

Agroforestry, a well-known sustainable land use approach according to (Dhakal and Rai, 2020), involves incorporating Poplar (*Populus deltoides*) plantings into various agroforestry systems. Poplar based Agroforestry system offers an alternate avenue for addressing climate change impacts and its mitigation due to contribute to increased biomass production and carbon storage which is the technological options for enhancing carbon capture, sequestration, and safeguarding carbon reservoirs according to (Kumar and Yadav, 2022; Nnko, 2022).

Populus deltoides W. Bartram ex Marshall is one of the most fast-growing species which has potential economically for wood production and environmentally for biomass production and carbon sequestration (Abedi *et al.*, 2023). Globally 4000 million area of Land under agroforestry which has potential to sequester 26 Tg Carbon by 2010 and 45 Tg Carbon by 2040 with mean carbon sequestration of 0.72 Mg $ha^{-1}yr^{-1}$ (Yadava, 2010).

The calculated net present value of carbon and its sensitivity analysis for price and carbon interest rate were found 180.2 m^3/ha (57.6 t/ha) with carbon content of 32.2 t/ha at the age 36 years the plantation stock which proved that the net present value depend upon the price and interest rate according to (Abedi *et al.*, 2022).

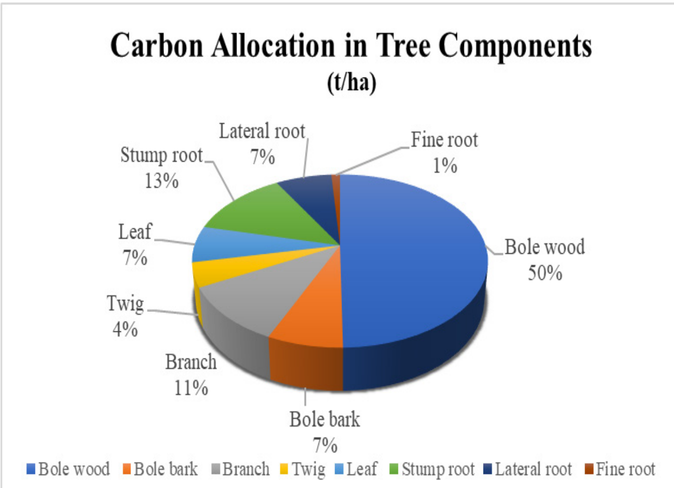

Figure 4: *Carbon allocation poplar tree components. (Singh and Lodhiyal, 2009b).*

The Figure 4 shows contribution percent of various component of 8-year-old Poplar (*Populus deltoides*) agroforestry plantation Poplar tree to carbon sequestration growing on farmlands are bole wood, bole bark, branch, twig, leaf, stump root, lateral root and fine root are 49.73% (47.85 t ha^{-1}), 7 % (6.74 t ha^{-1}), 10.61 % (10.21 t ha^{-1}), 4.53% (4.35 t ha^{-1}), 6.81% (12.43 t ha^{-1}), 12.92% (6.55 t ha^{-1}), 7.27% (6.99 t ha^{-1}) and 1.13% (1.08 t ha^{-1}) with total carbon stock of 96.23 t ha^{-1} according to (Singh and Lodhiyal, 2009).

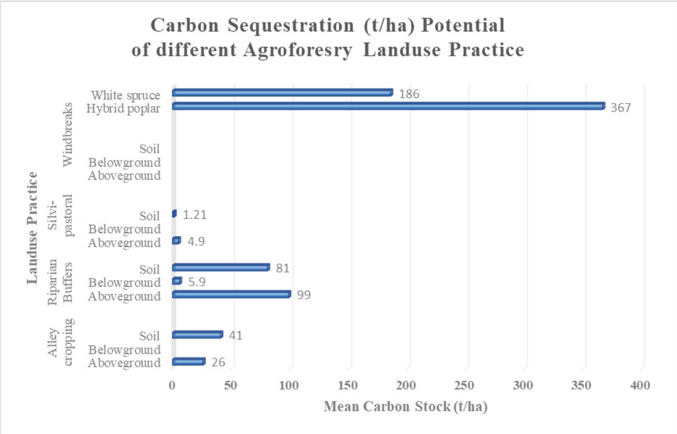

Figure 5: *Carbon stock of different agroforestry systems.*
Source: *(Kanwal et al., 2019).*

The predicted total carbon storage from existing alley cropping (211,938 hectares), riparian buffers (640,732 hectares), silvo-pasture (34 million hectares), and windbreak (2.37 million hectares) techniques amounts to 219 Tg yr^{-1}. The cumulative carbon storage could reach 240 teragrams per year through the adoption of additional practices, namely converting 5% of US cropland to alley cropping (yielding 3.7 Tg yr^{-1}), implementing 15-meter-wide riparian buffers on both sides of 5% of total stream length (resulting in 4.75 Tg yr^{-1}), transitioning 34 million hectares to silvopasture (contributing 207 Tg yr^{-1}), and establishing windbreaks on 5% of cropland (7.45 million hectares, producing 25 Tg yr^{-1}). The utilization of agroforestry based on poplar trees has demonstrated the augmentation of soil organic carbon and nitrogen stores in the soil according to (Sharma *et al.*, 2015). Soil carbon sequestration represents a significant method for carbon removal, and there is an increasing interest in policy and corporate circles to explore methods to incentivize farmers to enhance carbon sequestration efforts according to (Buck *et al.*, 2022).

The global stock of SOC in the top 1-meter layer of soil is approximately 1500 × 10^9 metric tons (t) which is a significant amount of carbon stored in the Earth's soil according to (FAO, 2017). Considered to be twice the amount found in the atmosphere indicating that soils are a crucial carbon reservoir, potentially helping mitigate the impacts of carbon dioxide in the atmosphere according to (Ali, 2020). About 40% of the world's SOC is present in forest ecosystems which underscores the significant role that forests play in sequestering carbon and highlights their importance in global carbon cycling and climate change mitigation efforts according to (Hudson *et al.*, 1994).

Gaps and challenges

An important deficiency in economic assessments is the omission of ecological and societal advantages and external impacts. Instances like offering compensation for ecosystem contributions or employing incentives to encourage farmers and land users to shift towards more socially beneficial land utilization exemplify this gap according to (Kay *et al.*, 2019).

Factors that have been recognized as impacting the adoption of agroforestry practices include how farmers view agroforestry, the socioeconomic circumstances they come from, and challenges such as unfavorable crop conditions, absence of viable markets, insufficient availability of nurseries, harm caused by human and animal activities, and a shortage of motivating incentives according to (Irshad *et al.*, 2011).

The main socio-economic factors influencing farmers' choices to encourage and embrace agroforestry techniques encompass household stability, availability of funds and rewards, workforce, gender roles, land ownership, farm dimensions, and managerial proficiency. While factors like landscape features, soil varieties, and climate play a role in plant growth, studies demonstrate that these socio-economic elements play a pivotal role in deciding whether agroforestry is implemented in practice according to (Glover *et al.*, 2013).

To effectively cultivate trees on their agricultural plots, there is a need for guidance and technical support, which currently lacks due to insufficient cooperation with the forest department. Farmers who do manage to incorporate trees into their farmland encounter challenges related to the marketing and transportation of their products according to (Nouman *et al.*, 2008).

Conclusions and Recommendations

Poplar based agroforestry system plays in mitigation of climate change by long term carbon storage and sequestration which considered cost effective sink for the reduction of greenhouse gas emission. The current economic review of the *Populus deltoides* concluded that average net return and average net present value are INR. 922,221 ha^{-1}, INR. 793,579 ha^{-1} with B:C of 2.45, respectively. The land expectation value, and land internal rate of return were found INR. 922,221 ha^{-1} and INR. 793,579 ha-with internal rate of return 52 % ha^{-1}.

It can be concluded that sustainable land use system can be achieved by Poplar based agroforestry systems which help in enhancing the biological yield (biomass), soil carbon and fertility as well as other ecosystem services from same piece of land. The socioeconomic factors are challenging for adaptation of Poplar based agroforestry system.

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Novelty Statement

In contrast to existing literature that predominantly focuses economic and mitigative aspects on the *Populus deltoides.*

Author's Contribution

Anwar Ali, Conceptualization, Ali Nawaz: Writing–original draft, Nowsherwan Zarif, Investigation, Asim Karim, Visualization, Qazi Bilal Ahmed: Writing–review Faizan Ahmad: editing and correction.

Conflict of interest
The authors declare no conflict of interest.

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