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Review

Fruit-based agroforestry for climate resilience in the northwest Himalayas

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ABSTRACT

Agroforestry offers a powerful, integrated solution for India, tackling critical issues like population growth, food security, resource degradation and climate change. This ancient yet revitalized practice serves as a vital carbon sink while boosting food production, providing income and fostering rural development. In the Indian Himalayas, fruit-based agroforestry is especially relevant. These systems effectively utilize limited and degraded lands, significantly increasing productivity and improving soil health (eg up to 99% runoff reduction with agri-horti-silvi-pastoral systems). They also enhance biodiversity and offer substantial economic benefits, including diversified income streams and considerable employment opportunities (estimated at 5.76 million person-days annually in the region), with high returns from systems like agri-silvi-horticulture. Despite this immense potential, challenges persist. These include limited and fragmented land, negative tree-crop interactions, inadequate extension services, topographical difficulties leading to erosion, a shortage of quality planting material and underdeveloped marketing infrastructure. High initial investment costs and poor logistics like cold storage further hinder widespread adoption. To unlock agroforestry's full benefits, future efforts must focus on efficient extension services, comprehensive farmer training, robust financial support and the integration of climate-smart practices. Developing supportive policies, mitigating topographical challenges (eg contour tree rows can reduce runoff by 40% and soil loss by 48%) and promoting multitier systems are crucial. Ultimately, strengthening marketing infrastructure and linkages is essential to ensure profitable returns for farmers and bolster the agricultural economy.

Keywords: Agroforestry; fruit-based systems; carbon sequestration; food security; challenges; solutions

INTRODUCTION

Agroforestry is truly a game-changer, offering a win-win for everyone. It's a land management system that acts like a sponge for carbon, pulling it right out of the air. At the same time, it helps us grow more food, provides a steady income for families and tackles pressing environmental issues (Zahoor 2021).

Here in India, our agriculture faces a tough road ahead. We've got a booming population, ever-increasing demands for food and animal fodder, dwindling natural resources and the undeniable impacts of climate change (Dhyani and Handa 2013). Looking ahead, climate change and rising temperatures will be our biggest hurdles to feeding everyone. Our farmers are particularly vulnerable, caught between the intertwined challenges of degraded resources and a changing climate. On top of that, the food we've been growing has taken a hit in quality over the past six decades. This is largely due to growing environmental concerns worldwide and the overuse of harmful pesticides, insecticides, weedicides and artificial fertilizers (Carvalho 2017).

And let's not forget our disappearing forests. Since 1990, a staggering 420 million hectares of forest have been lost to other land uses. While it's good news that the rate of deforestation has slowed – from 16 million hectares per year in the 1990s to an estimated

10 million hectares per year between 2015 and 2020 – the world has still lost over 80 million hectares of primary forest since 1990 (Anon 2020b). This all points to one clear need: we absolutely have to develop a management system that can feed our people, keep our soil healthy and fight climate change all at once. Agroforestry offers a promising path forward.

Agroforestry isn't just a buzzword; it's a smartly designed system that intentionally weaves trees and crops together, sometimes even with livestock, all on the same piece of land. More and more, it's being recognized as a truly sustainable way to boost what we grow while also protecting our environment (Catacutan et al 2017, van Noordwijk et al 2014). This isn't just about doing good; it's also about doing better, as this strategy improves how we manage our natural resources and makes our land more productive (Anshiso et al 2017).

Think of it as a brilliant fusion of age-old wisdom and cutting-edge science. In fact, it's an ancient practice that's making a big comeback, driven by a renewed scientific interest. Why now? Because we need solutions to meet the needs of a growing global population, keep our farming systems healthy and sustainable, halt the alarming rates of deforestation and soil degradation across the world's tropical and temperate zones and protect our precious biodiversity (Noble and Dirzo 1997, Mallick et al 2013).

Beyond its environmental perks, agroforestry is also seen as a fantastic engine for rural development. It's like a specialized intercropping system that allows farms to become more diverse and make smarter use of all the environmental resources available (Rahman et al 2013). Imagine a well-managed farm that integrates trees, crops and perhaps even animals – such a system can deliver incredible economic, social and environmental benefits (Kumar et al 2021).

One of the most effective ways to keep both crops and trees thriving and build a truly sustainable farm ecosystem is by integrating them on the same land through various agroforestry systems (Nair and Garrity 2012). What's fascinating is how they work together underground: tree roots tend to go deeper, tapping into water and nutrients that annual crops can't reach, while crop roots stay closer to the surface.

With our land becoming increasingly limited due to population growth, we can't just expand horizontally anymore. But with agroforestry, we can expand vertically by strategically planting deep-rooted trees alongside our agricultural crops, maximizing every inch of our land.

Agroforestry isn't new; it's a time-honoured tradition that has graced the landscapes of Himachal Pradesh for decades, evident in the trees proudly standing amidst the croplands (Pant et al 2022). As a deeply ingrained system of land use and resource management, it holds immense promise for securing livelihoods. It delivers vital ecosystem services like fodder for livestock, nourishing food, essential fuelwood, delicious fruits, valuable timber and a bounty of other non-timber forest products.

Beyond these tangible benefits, it also provides crucial environmental services such as protecting our watersheds, drawing carbon out of the atmosphere and shielding us from the harsh realities of climate change (Paustian et al 2016, Quli et al 2017).

When agroforestry is combined with smart practices like contour planting on sloped uplands, it becomes an incredibly effective land use system. It's a champion at curbing soil erosion and safeguarding the precious fertility of our soil (Roshetko et al 2017, Tacio 1993). Agroforestry ecosystems offer significant benefits to mountainous environments, particularly through their positive contributions to water, carbon, and nitrogen cycles, alongside their cultural and financial value. Expanding the nation's agroforestry areas could help address some key challenges posed by climate change (Anon 2015, Dhyani et al 2016).

In today's world, agroforestry is rightly gaining recognition as a truly sustainable way for farmers to manage their land. It's a system that not only offers them a diverse range of products but also actively helps mitigate climate change. From an economic perspective, this strategy of diversifying what farmers produce directly translates to increased income for them. This, in turn, leads to a significant improvement in their livelihoods and, ultimately, strengthens the entire nation's economy (Kaler et al 2022).

Imagine a farm where fruit trees stand tall, sharing the land with crops and even livestock – that's the essence of a fruit-based agroforestry system. Farmers thoughtfully choose fruit trees based on what thrives locally, what the soil offers and what the market demands. Alongside these trees, they might plant grains, vegetables or other cash crops and perhaps even raise sheep, goats or poultry.

Across the majestic Himalayan region, various agroforestry approaches have blossomed over the years, each tailored to specific needs and unique locations. This fruit-based system, in particular, is highly valued globally because of its strong market appeal and its vital contribution to our diets.

Beyond simply boosting agricultural sustainability and reducing risks for both small and large-scale farms, agroforestry offers a wealth of other benefits. It creates jobs, ensures access to nutritious food, helps reduce harmful greenhouse gas emissions, combats environmental pollution, improves the very health of our soil and contributes to overall economic stability (Sharma et al 2017b, Verma et al 2021).

These fruit tree-based agroforestry systems are especially powerful because they can fetch high market prices while also providing essential dietary needs for farmers in situations where resources are limited and land is scarce (Bellow 2004).

From digging into countless historical texts, it's clear that fruit-based agroforestry isn't some brand-new idea in the Himalayas or anywhere else; it's an ancient land-use practice that has been woven into the fabric of human societies for thousands of years. We can trace its roots back to ancient civilizations like Mesopotamia, India and China, where farmers intelligently combined trees with crops to get the most out of their land and resources.

Take southern Nigeria, for instance, where yams, maize, pumpkins and beans traditionally grew under the canopy of scattered trees (Forde 1937). The Yoruba people even credited this system with being an inexpensive way to keep soil fertile and fight erosion and nutrient loss (Ojo 1966).

In central America, for a very long time, farmers have skillfully planted dozens of plant species on plots as small as a tenth of a hectare. A farmer might layer coconut or papaya with a lower tier of banana or citrus, followed by a shrub layer of coffee or cacao, then annuals like maize and finally, a sprawling ground cover like squash (Nair 1993).

There are even reports of what we now call 'tropical homegardens' being linked to fishing communities in moist tropical regions as far back as 10000 BC (Nair and Kumar 2006). And if we look to Europe around 4000 BC, historical records describe trees being used in livestock systems – an early form of 'silvo-pastoralism', where trees provided shade for animals, improved the quality of their forage and supported sustainable livestock production (Mosquera-Losada et al 2012).

The true modern agroforestry movement really picked up steam in the mid-20th century. That's when researchers began to truly grasp its incredible potential to enhance food security, preserve our natural resources and champion sustainable land management. During this period, these integrated, often traditional ways of growing trees, crops and raising animals together were finally brought under the umbrella of modern scientific land use, proudly given the name 'agroforestry' (Nair et al 2021).

Existing fruit-based agroforestry system in northwestern Himalayas

In fruit-based agroforestry systems, it's interesting because the trees themselves are the star players, the main crops. The other plants – whether they're annuals or woody or non-woody perennials – are grown beneath or between these main fruit trees, benefiting from their shade. Nature is full of these clever plant partnerships, but some have truly taken off as prominent land use systems because of the economic and commercial value of the species involved.

With the growing realization that we need to make the most of our land due to rapidly increasing populations, people are increasingly turning to integrated production systems that cleverly combine fruit crops, livestock and traditional agricultural crops. In fact, by 2025, it's projected that a substantial 25.36 million hectares could be under agroforestry in a moderate scenario. Roughly half of this area is expected to be dedicated to tree-borne oil seeds, with horticulture and other crops making up the rest (Anon 2007).

The western Himalayas, in particular, are essentially an agro-ecosystem. A remarkable 90 per cent of the population lives in villages, where farming, fruit growing and animal husbandry are their primary sources of income (Atul and Khosla 1994).

Planting fruit trees on farms isn't just about making money; it also helps farmers meet their crucial nutritional needs. The wisdom of agroforestry has always been a go-to solution for rural livelihoods in the Himalayas, a fact clearly seen in the trees carefully maintained on farm boundaries. To really push these efforts forward with strong scientific backing, various initiatives have been launched, propelling India to the forefront of agroforestry research (Anon 2013).

Implementing these agroforestry practices isn't a one-size-fits-all solution; it depends on things like soil quality, climate, socio-economic factors and what individual farmers need. The way these systems are managed also varies based on physical features of the land, population aspects and even institutional support (Bayard et al 2007).

Despite these variables, numerous fruit-based agroforestry frameworks have been developed, each perfectly adapted to the unique needs and specific characteristics of different localities throughout the Himalayas (Yadav and Bisht 2014). In the Himalayan region, there's plenty of evidence in literature showcasing a rich variety of fruit-based agroforestry combinations. These include agri-horticulture, agri-horti-silviculture, hort-isilviculture and agri-silvi-horticulture, demonstrating the diverse and effective ways farmers integrate fruit trees into their land management (Mazumdar 1991, Sood 1999, Thakur 2020, Chauhan et al 2011, Kumari et al 2008, Bhagat et al 2006).

Climate change mitigation and adaptation through carbon sequestration in fruit-based agroforestry systems

The United Nations Framework Convention on Climate Change (UNFCCC) defines carbon sequestration as the vital process of pulling carbon (C) out of the atmosphere and safely tucking it away in storage, essentially moving atmospheric CO_2 into long-term pools (Anon 2008).

This is critical, as projections from the Intergovernmental Panel on Climate Change (Anon 2000) warn that average global temperatures could increase by a concerning 1.4 to 5.8°C by the year 2100. While activities like vegetation fires and clearing land for agriculture and forestry release significant CO_2 into the atmosphere, much of this is often reabsorbed by subsequent plant regrowth (Lorenz and Lal 2010, Nair et al 2010).

In land use systems that incorporate trees, a remarkable 60 per cent of the carbon is stored in the soil, with another 30 per cent held in the parts of the plants above ground (Lal 2005, 2008).

This is why agroforestry stands out as a powerful strategy to combat climate change, thanks to its incredible ability to sequester carbon in various plant species and soils (Albrecht and Kandji 2003, Anon 2006). When trees are integrated into croplands and pastures, it's believed to significantly boost net carbon storage both above and below ground, making agroforestry systems far more effective at carbon sequestration compared to simply having pastures or field crops (Kirby and Potvin 2007, Roshetko et al 2002, Montagnini and Nair 2004, Nair et al 2009a, 2010, Nair and Nair 2014).

Indeed, agroforestry shows immense promise for locking away carbon, both below and above the ground (Goswami et al 2014). Imagine planting fruit trees alongside timber trees within our agricultural systems – this approach has the potential to dramatically increase carbon storage on farmland. It allows us to grow food crops while simultaneously cultivating valuable fruit and timber trees (Kürsten 2000).

These innovative agroforestry frameworks help reduce climate change in two key ways: indirectly, by limiting deforestation and directly, by accumulating carbon in the above-ground parts (like leaves, stems and branches) and below-ground biomass (roots), as well as within the soil itself (Jose and Bardhan 2012, Zomer et al 2016).

Compared to a single-crop field or a pasture, the amount of carbon sequestered can significantly increase just by adding trees or shrubs to an agroforestry system (Kirby and Potvin 2007). It's estimated that agroforestry has the capacity to sequester a massive 2.1×10^9 Mg C per year in tropical areas and 1.9×10^9 Mg C per year in temperate regions, just in the above-ground biomass (Oelbermann et al 2004).

Furthermore, various fruit-based agroforestry practices deliberately expand the soil organic carbon (SOC) pool, which is our planet's only terrestrial carbon reservoir (Lorenz and Lal 2014). Soil plays a central role in the global carbon cycle, with the soil carbon pool, including SOC, estimated at 1550 gigatons (Gt) and soil inorganic carbon at about 750 Gt, both measured down to a depth of 1 meter (Batjes 1996). Any shifts in this soil carbon pool can have substantial impacts on the global carbon budget (Smith et al 2020).

Historically, terrestrial ecosystems have released approximately 136 ± 55 Pg of CO_2-C into the atmosphere, with soils contributing a significant 78 ± 12 Pg (Lal 2008). The loss of organic carbon from tropical soils doesn't just increase atmospheric CO_2 levels; it also unfortunately depletes the fertility of already nutrient-poor soils (Nair and Nair 2003).

The good news is that effective management practices can help restore at least some of this lost carbon (Lal et al 2018). In terms of SOC content, land use systems typically rank in this order: Forests >Agroforests >Tree plantations >Arable crops (where agroforests are complex, multi-layered systems similar to home gardens but larger in scale (Nair et al 2009a, 2009b). Changes in the productivity of plants both above and below ground, alterations in root depth and distribution and variations in the quantity and quality of organic matter inputs all influence carbon dynamics and storage within these ecosystems.

In the Indian Himalayas, we've seen a beautiful transformation where extensive fruit tree plantations have evolved into thriving agroforestry systems. These systems are absolutely vital for the Himalayan region. In our current climate, life would be incredibly challenging without such sustainable agroforestry land use practices.

The tree components not only fight climate change by sequestering carbon above and below ground, but they also protect crops from harsh weather, help retain crucial moisture, reduce the risk of landslides and improve soil fertility by adding leaf litter or fixing nitrogen (Yadav et al 2015, Koul and Panwar 2008).

Researchers in the Himalayas have observed and documented various combinations of fruit-based agroforestry systems and significant work is being done to quantify the carbon sequestration potential of different systems, such as agri-horticulture and agri-horti-silviculture, across four distinct agro-climatic zones of the Himalayas, measuring both above and below ground carbon and in organic soil.

Economics of fruit-based agroforestry systems

Agroforestry offers a wealth of ecological benefits and what's more, it has a remarkable ability to uplift low-income households (Shukla et al 2018). With India's rapid urbanization and economic growth, farming communities now have an unprecedented chance to supply agricultural products beyond just meeting their own needs (Anon 2020a).

Beyond the direct financial gains, agroforestry holds immense potential for creating jobs and significantly improving the livelihoods of those who depend on agriculture (Pant et al 2022, Mirjha and Rana 2016). In fact, the presence of trees outside traditional forest areas, fostered through agroforestry and social forestry initiatives, has substantially boosted the country's GDP from 1 per cent to an impressive 1.70 per cent (Anon 2010).

Specifically, in the Indian Himalayan region, agroforestry has the potential to generate a remarkable 5.76 million person-days of employment annually (Dhyani and Sharda 2005). This means agroforestry could be a powerful tool for the state government in its aim to reduce unemployment from 10.6 to 6 per cent (Anon 2021).

Within this sustainable farming system, integrating livestock acts as a vital safety net, providing a steady income to households even when crops fail due to climate change, insect attacks or other pests (Sharma et al 2008).

The choice of tree species for agroforestry usually depends on cultural values, economic considerations and environmental factors. However, by incorporating certain principles of photosynthesis into the selection process, we can actually boost the overall productivity of these systems, leading to even greater economic returns (Sharma et al 2008, Nair 1993).

When fruit trees are integrated with agricultural crops in mountainous regions, the benefits truly multiply. This agri-horticulture system has consistently shown the highest overall benefits across various altitudes (Chisanga et al 2013). For example, a survey by Sharma (2022b) in Sujanpur Tehsil of Hamirpur district revealed that among all types of farmers, the highest net returns (Rs 297,581.20 per hectare per year) were reported from agri-silvi-horticulture (ASH) systems, while silvi-pastoral (SP) systems had the least (Rs 5,772.50 per hectare per year).

Another survey by Sharma (2022a) in Jogindernagar Tehsil of Mandi district showed that agri-silvi-horticulture (ASH) systems again yielded the highest net returns (Rs 99,405 per hectare per year). Furthermore, the agri-horticulture (AH) system recorded an impressive benefit-cost ratio of 2.83.

Practical suggestions, such as those from Verma and Thakur (2010), highlight the potential for increased productivity and profitability by cultivating medicinal plants like Ashwagandha (*Withania somnifera*) alongside peach trees, or even with *Morus alba* fruit trees and setaria grass.

Impact and contribution of fruit-based agroforestry system

Making the most of every inch: Imagine land that's tough to farm – perhaps it's degraded or just not ideal for traditional crops. Fruit-based agroforestry steps in as a smart solution. By using approaches like horti-pastoral (fruit trees with pasture) or horti-silvi-pastoral (fruit trees, timber trees and pasture), we can actually make these challenging sites productive. Not only do these systems help provide much-needed fodder for animals, but they're also champions at protecting the soil and boosting its fertility. Plus, by strategically planting trees and creating windbreaks, they help the land hold onto precious moisture and reduce how much water plants lose, making everything more resilient.

Boosting what we grow: Studies have consistently shown that for farmers, agroforestry can be a more profitable venture than simply sticking to conventional farming or just planting forests on certain areas of land. Take, for example, an *Emblica officinalis* (Amla)-based agroforestry system on marginal, rainfed lands. After just 13 years, the benefits outweighed the costs by 3.28 times and even when accounting for future value, it was still a solid 2.61 – clear proof that it's a profitable enterprise (Newaj and Rai 2005).

Healthy soil, healthy planet: Agroforestry isn't just about growing things; it's about growing them right. Ecologically sound practices like intercropping (planting different crops together) and mixed farming systems (integrating crops and livestock) are fantastic for bringing organic matter back into the soil, making it healthier and more fertile and truly boosting agricultural sustainability. In fact, comprehensive systems like agri horti-silvi-pastoral can reduce harmful runoff by an incredible 99 per cent (Singh 1988).

Protecting our planet's treasures: One of the biggest challenges we face is the over-exploitation of our natural resources, threatening both sustainable production and our very livelihoods. Agroforestry offers a lifeline. By combining timber trees, fruit trees, agricultural crops, grasses, livestock and more, it provides a heaven for all sorts of life. These systems are crucial for conserving biodiversity, offering a safe refuge for various species, especially after devastating events like fires (Griffith 2000).

Addressing social needs: Beyond the environmental perks, embracing fruit-based agroforestry genuinely improves people's lives. It brings in extra income and provides vital livelihood support, offering a cushion for families. And the produce from these trees ensures nutritional security, which is especially critical for the well-being of women and children.

Our climate ally: By weaving fruit trees together with timber trees in our farming systems, we're actively helping to fight climate change. This practice directly contributes to carbon sequestration, meaning more carbon is pulled from the atmosphere and stored in our agricultural lands. All the while, we can continue to cultivate essential food crops (Kürsten 2000).

Constraints

While agroforestry offers incredible promise, it's important to acknowledge the real-world hurdles that can make its widespread adoption challenging.

Limited land: In mountainous regions like Himachal Pradesh, simply finding enough suitable land is a big problem. The terrain is often steep and with a growing population, available land is fragmented into tiny plots. Picture this: almost 90 per cent of landholdings are small or marginal, averaging less than a hectare (Anon 2021). This makes it tough to implement large-scale agroforestry systems.

Tree-crop conflicts: It's not always a perfect harmony. Sometimes, the shade from tree canopies can actually hurt the performance of crops growing beneath them. Research has shown these negative interactions, which means careful planning and species selection are crucial (Kaushal and Verma 2003, Garima and Pant 2017, Kaur et al 2017, Pratap and Pant 2020).

Inadequate extension activities: We have valuable agroforestry research, but getting that knowledge into the hands of farmers is a major bottleneck. The system for sharing this information is often inefficient, largely because there isn't a strong institutional framework to support it (Anon 2014, Tiwari et al 2018). Plus, there's no single recipe for on-farm research; it has to be tailored to each unique situation, which adds to the complexity (Nair 1993).

Mountainous terrain: Himachal Pradesh is, by nature, a hilly state, with altitudes soaring from 350 to almost 7,000 meters amsl (Anon 2019). A whopping 70 per cent of the state has steep to very steep slopes (Gupta et al 2017). These steep gradients naturally increase soil erosion, causing problems not only on the immediate farmland but also in surrounding areas.

Finding good quality trees: The very backbone of any agroforestry system is the trees and unfortunately, there's a serious shortage of high-quality planting material. The demand for various tree seedlings is enormous – millions each year – yet only about 10 per cent of what's available is considered high quality, leaving farmers with uncertain options (Handa et al 2019, Chavan et al 2015, Anon 2014). If you can't get good trees, it's hard to build a good system.

Marketing maze: Once farmers produce their agroforestry goods, selling them can be a challenge. With a few exceptions, India generally lacks proper marketing infrastructure for these products, including clear ways to determine fair prices (Anon 2014).

No crystal ball for markets: Without a reliable market information system, farmers are often guessing about demand and supply trends. This uncertainty can lead to losses if they produce too much or too little of something at the wrong time (Pant et al 2022).

The unpredictable climate: Climate change is a constant threat. Shifting seasonal patterns, unpredictable temperature changes and altered rainfall and snow patterns can directly impact the growth and yield of fruit trees, adding another layer of risk for farmers.

High upfront investment: Setting up an agroforestry system often requires a significant initial investment, which can be a major deterrent for many farmers, especially those with limited resources.

Poor logistics: Even if they manage to produce, inefficient transport and a lack of proper cold storage facilities mean that perishable fruit and other produce can spoil before it reaches the market, leading to wasted effort and lost income.

Future perspectives

Let's look ahead and imagine a future where fruit-based agroforestry truly flourishes, overcoming its current challenges and becoming a cornerstone of sustainable agriculture.

Bridging the gap: We need to supercharge the way we share knowledge. Imagine seamless communication channels and strong collaborations that act as bridges, taking cutting-edge research from the labs directly to the fields. This will empower farmers to hit their personal goals and contribute to national sustainable development goals.

Empowering farmers: Education is key. We need to run hands-on training programmes that teach farmers the ins and outs of best agroforestry practices. This includes everything from proper tree planting and pruning techniques to smart pest management and showing them various combinations of crops that thrive alongside fruit trees in diverse agro-climatic zones, leading to truly sustainable land management.

Financial support: Let's make it easier for small-scale farmers to jump on board. This means offering financial incentives, subsidies or low-interest loans to help them cover the initial setup costs of fruit-based agroforestry systems. By easing this financial burden, we can encourage many more farmers to participate and reap the benefits.

Climate-smart practices: We must integrate climate-smart practices directly into fruit-based agroforestry systems. Think innovative water conservation techniques, strategic mulching, targeted fertilization and integrated pest management. While we can't stop climate change entirely, these practices will significantly boost the resilience of these systems, making them less vulnerable to extreme weather events and helping us minimize environmental impact.

Policy support: Strong policies and regulations are crucial. We need governments to develop and implement supportive frameworks that actively promote and incentivize fruit-based agroforestry. This could involve offering tax incentives, ensuring secure land tenure for farmers and formally recognizing agroforestry as a vital part of national agricultural strategies.

Mitigating topographical challenges: The Himalayas' steep slopes don't have to be a barrier. By adopting clever soil erosion control measures and smart planting techniques, we can turn these topographical challenges into opportunities for profit (Sharma et al 2017a). Studies show that simple yet effective agroforestry practices, like planting contour tree rows (or hedge rows), in the western Himalayas can dramatically reduce runoff by 40 per cent and soil loss by a significant 48 per cent (Pandey 2007).

Fruit-based multitier systems: Picture a system where every piece of land gives back more. Fruit-based multitier systems do just that, boosting total production per unit of land. They offer a diverse array of products, provide year-round employment, ensure stable income, help spread financial risk and ultimately contribute to self-sufficiency (Dhakar et al 2024). This approach is especially valuable in regions like the Shivalik, where erosion is a major culprit behind soil degradation and nutrient depletion (Grewal 1993).

Developing infrastructure and linkages: For all this hard work to pay off, farmers need access to effective and competitive markets. This means building suitable post-harvest and marketing infrastructure, ensuring that products can be processed, stored and transported efficiently. The ultimate goal is to connect farmers directly to consumers, guaranteeing them a net positive return on their efforts (Anon 2018).

CONCLUSION

Agroforestry stands as a compelling and indispensable solution for India's multifaceted agricultural and environmental challenges. It's a system deeply rooted in ancient wisdom, now invigorated by modern science, offering a holistic approach to sustainable land management. The evidence overwhelmingly demonstrates its capacity to act as a vital carbon sink, significantly contributing to climate change mitigation, while simultaneously bolstering food security, enhancing farmer livelihoods and preserving crucial biodiversity.

In regions like the Indian Himalayas, where agriculture is the lifeblood of 90 per cent of the population, fruit-based agroforestry systems prove particularly effective. They efficiently utilize limited, often challenging, land, boost overall productivity and provide substantial economic benefits, including increased income and employment generation. The positive impact on soil health, through organic matter restoration and erosion control, is equally profound, highlighting agroforestry's role in maintaining ecological balance.

However, the path to widespread adoption is not without its obstacles. Constraints such as fragmented landholdings, potential tree-crop competition, insufficient extension services, difficult mountainous terrain, a shortage of quality planting material and weak market infrastructure present significant hurdles. Financial limitations, particularly high upfront costs and inadequate cold storage, further complicate matters for farmers. Looking ahead, realizing the full potential of agroforestry demands a concerted, multi-pronged effort. This includes strengthening extension services to bridge the gap between research and practice, investing in comprehensive farmer training and capacity building and providing much-needed financial support to reduce initial investment barriers.

Integrating climate-smart practices will enhance resilience, while supportive policies and regulations are crucial for mainstreaming agroforestry into national agricultural strategies. Furthermore, targeted interventions to mitigate topographical challenges and the development of robust marketing infrastructure and linkages are essential to ensure economic viability for farmers. By addressing these constraints strategically and investing in these future perspectives, India can truly harness the power of fruit-based agroforestry. This will not only secure food and livelihoods for its growing population but also create a more resilient, environmentally sound and economically vibrant agricultural future.

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