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Innovations in STEAM: Research & Education

ABOUT

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Crop Rotations: Effects on Soil Health and System Productivity

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ABSTRACT

Background: Crop rotation (CR) is a key conservation practice for sustaining soil health and productivity, but evidence on its effects is scattered across many soils, crops and climates.

Objective: To review how CR influences soil physical, chemical and biological characteristics and the productivity of cropping systems.

Methodology: Published field and long-term studies on rotations of cereals, legumes, vegetables and oilseed crops were reviewed and synthesised under soil physical, chemical, biological and productivity headings.

Results: Diversified rotations, particularly those including legumes and forage crops, generally reduced bulk density and improved porosity and hydraulic properties, although short-term trials showed little effect on macroporosity. Such rotations increased soil organic carbon (by up to 22% over maize–wheat), total nitrogen, available nutrients, exchangeable bases and enzyme activities (dehydrogenase by 52–79%). Rotation affected soil pH, electrical conductivity and cation exchange capacity in a system- and depth-dependent manner. Longer rotations reduced weed cover (from 40% to 20%) and soil-borne diseases (by 10–52%), and diversified rotations improved the robustness of crop productivity by 14%.

Conclusion: CR is an effective, multi-benefit strategy for sustainable soil management. Responses depend on crop sequence, soil type and duration, and the microbial mechanisms of disease suppression need further study.

INTRODUCTION

The colloquial use of the term “rotation effect” has a long history in agronomic research. Crop rotation (CR) and residue incorporation are recommended techniques for building conservation agriculture with minimal soil disturbance, which concurrently conserve soil and water while reducing input costs (Jiang *et al.* 2011; Zhang *et al.* 2018). Residue retention and CR enhance soil quality by reducing soil breakdown, controlling soil erosion, increasing the soil infiltration rate, improving nutrient cycling and soil organic carbon, and protecting the soil from raindrop impact (Dube *et al.* 2012; Zhang *et al.* 2018; Struijk, 2026). Rotation effects are expressed in the physical, chemical and biological components of soil health and, ultimately, in the productivity of the whole cropping system. For example, Borase *et al.* (2020) found that a pigeon pea–wheat rotation

had 15% higher soil respiration than a maize–wheat rotation. The objective of this review article is to review the effects of CR on soil physical characteristics: hydraulic properties, bulk density and porosity; to synthesize evidence on soil chemical and biological responses to CR: organic matter, nutrients, pH, electrical conductivity, cation exchange capacity, exchangeable bases, enzymes and microbes and to examine the effects of CR on weed and disease management and on system productivity

CROP ROTATION AND SOIL PHYSICAL CHARACTERISTICS

Soil hydraulic properties

CR strongly influences soil hydraulic properties. Soils with low porosity and high bulk density have a negative impact

on the infiltration rate and saturated hydraulic conductivity (Bhattacharyya *et al.* 2006; Miriti *et al.* 2013). In this regard, Dexter *et al.* (2001) included a mustard or clover–grass mixture in the rotation and found higher hydraulic conductivity in a loamy sand soil in Poland. In another study, Głab *et al.* (2013) compared the long-term effect of CR on the hydraulic properties of a loam soil under different cropping systems: winter triticale–spring triticale; spring triticale–winter triticale–oat; and sugar beet–spring triticale–faba bean–winter triticale. They observed that water retention properties were significantly enhanced by rotation, especially with triticale, which increased the quantity of available water. However, the crop effect was not stable, and longer-term CR did not prove beneficial. McVay *et al.* (2006) investigated the effects of CR and tillage in five long-term trials on silt loam soils in Kansas, USA, and noted changes only in the upper soil layer (0–5 cm). Blair *et al.* (2006) reported that long-term CR on two clay-rich Vertosols under semi-arid conditions in Australia changed the aggregate mean weight diameter and hydraulic conductivity by increasing soil organic carbon, especially with more frequent inclusion of forage legumes (*Medicago sativa* L.) in the rotation (Fig. 1-2)

Armstrong *et al.* (1999) reported that, in a legume-to-sorghum rotation, higher hydraulic conductivity was associated with significantly improved macroporosity of a clay soil. Studies of CR clearly demonstrate that roots are directly involved in improving hydraulic activity at the field scale (Dexter *et al.* 2001). Similarly, Pala *et al.* (2007) indicated that an improved biennial rotation with wheat is imperative for better yield and improved water-use efficiency. Wei *et al.* (2020) reported that soil water content was significantly higher under a lentil–wheat–maize rotation (9.81%) than under a wheat–maize–potato rotation (8.43%). Based on 40 years of observation, they suggested a key role of CR in changing soil water content.

Overall, the evidence indicates that CR is an effective way to improve soil hydraulic properties, though the size and persistence of its benefits depend on soil type, crop sequence, and duration. Rotations that include legumes, forage species, or deep-rooted crops generally increase soil organic carbon, aggregate stability, and macroporosity. These changes raise hydraulic conductivity and improve water retention and available water, as shown in loamy sand, loam, and clay-rich Vertisol soils. The benefits are often strongest in the surface layer, are not always stable over time, and may not increase with longer rotation periods. Rotations that include legumes also increased soil water content over the long term and supported higher yield and water-use efficiency. Roots appear to be the main driver of these improvements at the field scale. Well-designed, site-specific rotations that combine legumes and cereals are therefore a sustainable strategy for improving soil structure, water availability, and resilience, particularly in water-limited environments. However, multi-site research is needed to clarify the mechanisms and the stability of these

effects under different environmental conditions.

Soil bulk density

Karlen *et al.* (2006) found that extended CR including legume, forage and oat reduced soil bulk density compared with continuous corn and corn–soybean rotation. Shaver *et al.* (2003) observed that sorghum–wheat and corn–wheat rotations had lower bulk density and higher soil porosity than continuous wheat. Stone and Silveira (2001) reported the highest bulk density in a soybean–wheat rotation relative to other combinations. Likewise, Wei *et al.* (2020) found that soil bulk density was significantly higher under lentil–wheat–maize (1.19 Mg m^{-3}) than under wheat–maize–potato (1.16 Mg m^{-3}). Similarly, Degu *et al.* (2019) found that land under maize–wheat–faba bean had a higher mean bulk density (1.06 g cm^{-3}) than land under other rotations ($1.02\text{--}1.04 \text{ g cm}^{-3}$).

Taken together, these studies indicate that diversified rotations, particularly those that include forage or legume phases, tend to reduce bulk density relative to monocultures or short two-crop sequences. However, the magnitude of effect is often small and varies with crop identity, so rotation design should match the specific soil and cropping context.

Soil porosity and aeration

Natural cracking, soil faunal activity and macropores created by previous root growth can provide better pathways for root growth of the following crop; otherwise, hard soil layers restrict root growth and nutrient availability. The beneficial consequences of such pores depend on their strength in the soil matrix, their frequency and size, and nutrient and water availability (Ball *et al.* 2005).

Nebo *et al.* (2020) reported that maize following maize had the highest bulk density (1.4 g cm^{-3}), compared with a maize–wheat–maize rotation (1.36 g cm^{-3}), and the lowest bulk density was observed in the maize–soybean rotation (1.29 g cm^{-3}). The authors further concluded that the interactions of CR $\times$ tillage, tillage $\times$ residue management and CR $\times$ residue management were non-significant ($p > 0.05$) and had no impact on water-conducting macroporosity and hydraulic conductivity. They suggested that CR had little effect on macroporosity in the short term (3 years). Recently, Singh *et al.* (2020) examined the effect of a 2-year maize–soybean rotation and a 4-year maize–soybean–oat–winter wheat rotation on the near-surface pore characteristics of a silty clay loam under field conditions. They noted that the 4-year rotation increased the number of pores measured by X-ray computed tomography, coarse mesopores ($226\text{--}1000 \text{ }\mu\text{m}$ diameter), macropores ($>1000 \text{ }\mu\text{m}$ diameter), macroporosity and mesoporosity compared with the 2-year maize–soybean rotation. In addition, Fuentes *et al.* (2009) reported a greater water infiltration rate and pore frequency in wheat than in corn-dominated rotations.

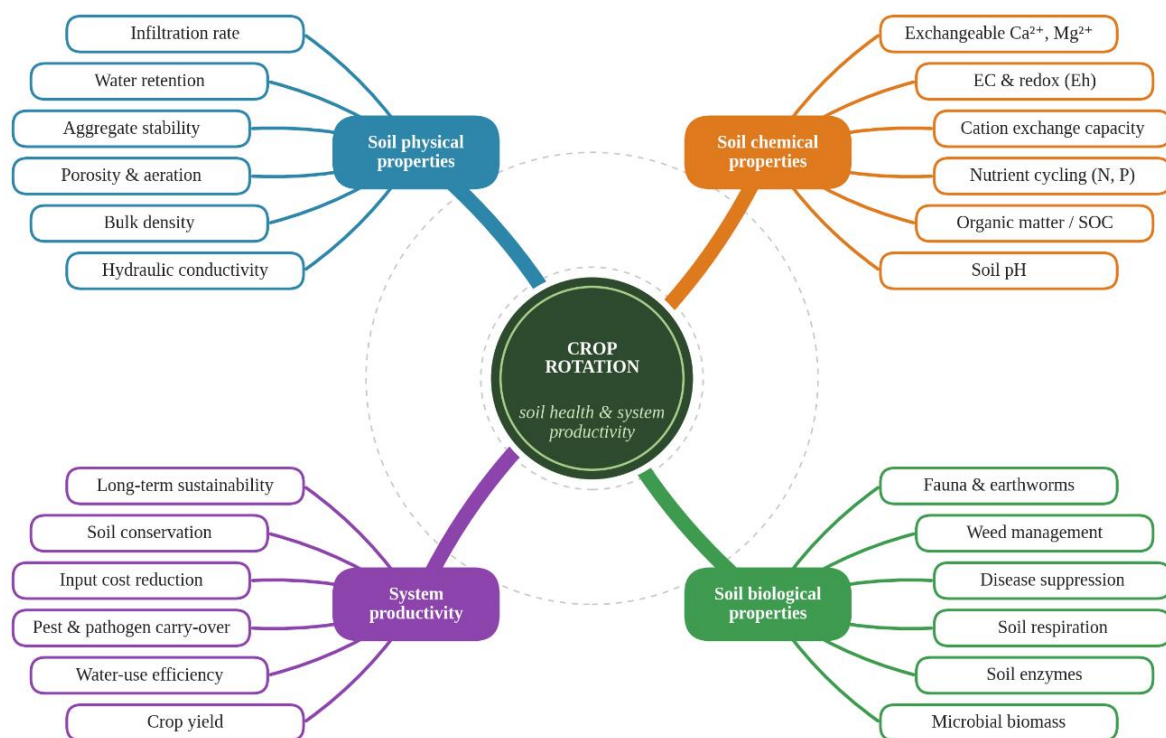


Fig 1: Crop rotation effect on soil physical, chemical, biological and system productivity

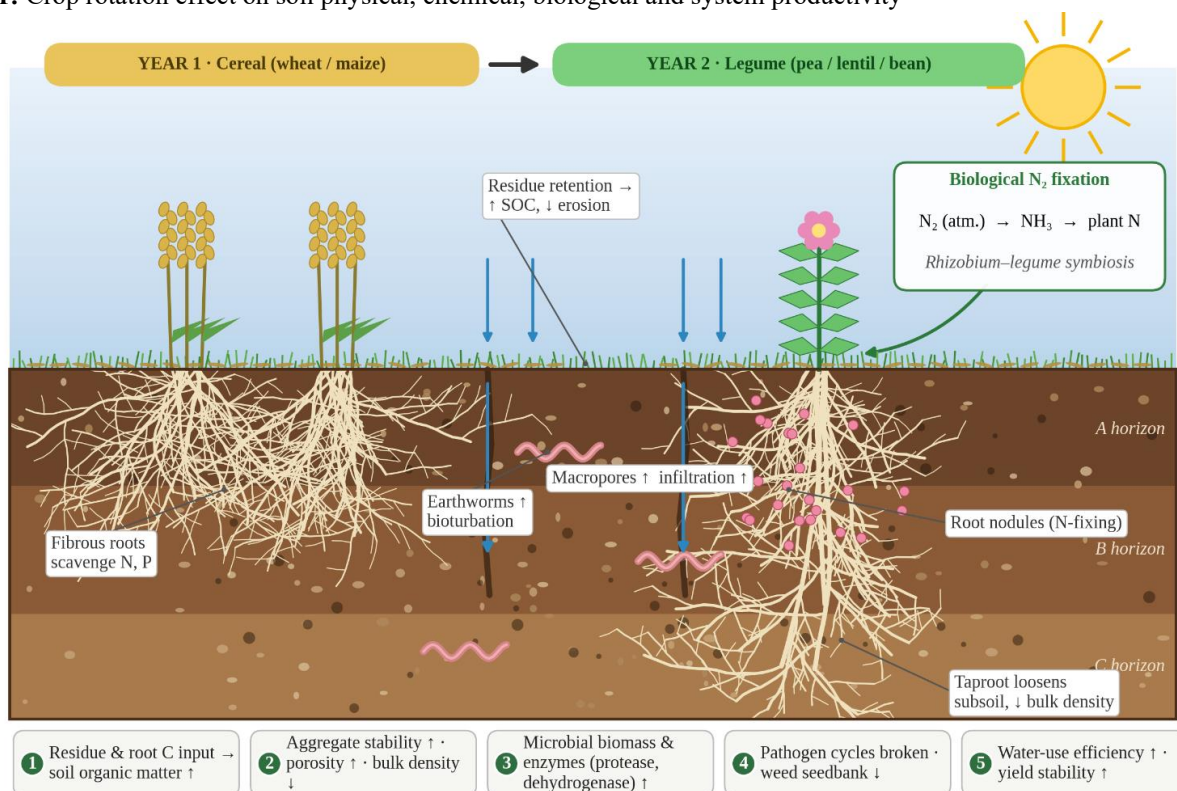


Fig. 2: Soil cross-section comparing a cereal year with a legume year.

Stone and Silveira (2001) confirmed that a rotation of upland rice with common bean and calopogonium showed the highest macroporosity and the lowest microporosity compared with the other rotation systems, including corn–common bean, soybean–wheat–soybean–common bean and upland rice–common bean, whereas the highest microporosity and lowest macroporosity were observed in soybean–wheat. Similarly, Bodner *et al.* (2014) provided evidence for the impact of cover crops on soil pore size distribution. They found that root axes had a distinct effect on hydraulic properties and that root growth influenced different pore size classes, with fine root systems dominating in brassica and coarse root systems in legume crops.

In summary, the evidence indicates that rotation influences soil pore structure mainly through the rooting traits of the crops involved, and that measurable changes in macroporosity are more likely under longer, more diverse rotations than over short experimental periods.

CROP ROTATION AND SOIL CHEMICAL CHARACTERISTICS

Soil pH and cation capacity determine the chemical state of soil, which in turn affects microbial activities and has direct consequences for soil health and environmental quality.

Soil organic matter dynamics

Diversified rotations have an almost consistently positive effect on soil organic matter (OM), which improves soil health in all respects. Charman and Roper (2007) found a higher soil OM content on all land rotated with cereals and legumes. The highest OM was found in maize–pepper–pepper and maize–wheat–pepper rotations, at about 5.12% and 5.05%, respectively (Degu *et al.* 2019). The authors suggested that this is likely due to the slow decay of the biomass and roots of pepper through various forms of active soil OM, which supply nutrients slowly and stabilise soil aggregates. Huang *et al.* (2002) similarly noted that, since organic carbon and total N are stoichiometrically linked in soil OM, greater OM invariably led to an increase in N and organic carbon in rotations where faba bean and pepper were included over time.

Singh *et al.* (2020) found that the 4-year maize–soybean–oat–winter wheat rotation had 4%, 14% and 16% higher wet aggregate stability, total nitrogen and soil organic carbon, respectively, than the 2-year maize–soybean rotation. According to Karlen *et al.* (2006), extended CR with legume, forage and oat increased soil organic carbon and wet aggregate stability compared with continuous corn and corn–soybean rotation. In contrast, including soybean in a short rotation with corn has been found to lead to lower soil organic carbon than corn monoculture, owing to lower residue production and rapid residue decomposition of soybean (Coulter *et al.* 2009; Benjamin *et al.* 2010).

Bhattacharyya *et al.* (2009) showed that soybean–pea and soybean–lentil rotations had higher soil organic carbon than soybean–wheat only in the whole-soil fraction (<4.57 mm) at 0–15 cm depth.

Borase *et al.* (2020) observed the following order of rotations for soil organic carbon: pigeon pea–wheat > maize–wheat–mung bean > maize–wheat–maize–chickpea > maize–wheat. They reported that maize–wheat–mung bean and pigeon pea–wheat rotations increased soil organic carbon by 12% and 22%, respectively, over maize–wheat during 13 years of experimentation. Degu *et al.* (2019) found that mean soil organic carbon was significantly higher under maize–pepper–pepper (2.97%), followed by maize–wheat–pepper (2.93%), and lowest under continuous maize (2.63%). McDaniel *et al.* (2013) recommended legume and crop rotation to increase soil carbon and N by up to 3.6% and 5.3%, respectively, compared with monoculture.

Diversified rotations that include legumes, forages or high residue crops generally raise soil organic matter, organic carbon, total nitrogen and aggregate stability, and the gains tend to increase with rotation length and crop diversity. The benefit is not universal, however, because short sequences dominated by low-residue crops such as soybean may give little or no improvement, and can even lower soil organic carbon relative to continuous corn. Rotation design should therefore emphasise crops that return substantial and slowly decomposing residues.

Nutrient cycling

According to Malobane *et al.* (2020), CR and residue incorporation increased ammonium, nitrate, calcium, potassium and cation exchange capacity. Alemayehu *et al.* (2020) studied the potential of CR for restoring the productivity and health of degraded highland crop fields and confirmed higher exchangeable potassium, available phosphorus and total nitrogen. Laamrani *et al.* (2020) reported that diversified CR increased the total carbon concentration of soil. The highest carbon content was found in the corn–corn–oat–barley rotation with red clover as a cover crop in both cereal phases. The authors noted a descending order for corn–corn–alfalfa–alfalfa and corn–corn–soybean–winter wheat with one year of seeded red clover, followed by continuous corn. The lowest total carbon concentrations were noted in corn–corn–soybean–soybean and corn–corn–oat–barley without red clover as a cover crop, and in corn–corn–soybean–winter wheat. Plots under soybean–lentil and soybean–pea rotations had about 19% and 21% higher total soil nitrogen, respectively, than soybean–wheat (Bhattacharyya *et al.* 2009). In addition, Haruna and Nkongolo (2019) found a significant improvement in total carbon ($p = 0.0304$) under corn–soybean rotation compared with continuous soybean and continuous corn during a 3-year study. According to Wei *et al.* (2020), based on 40 years of observation, soil organic carbon did not differ significantly between the 20-year

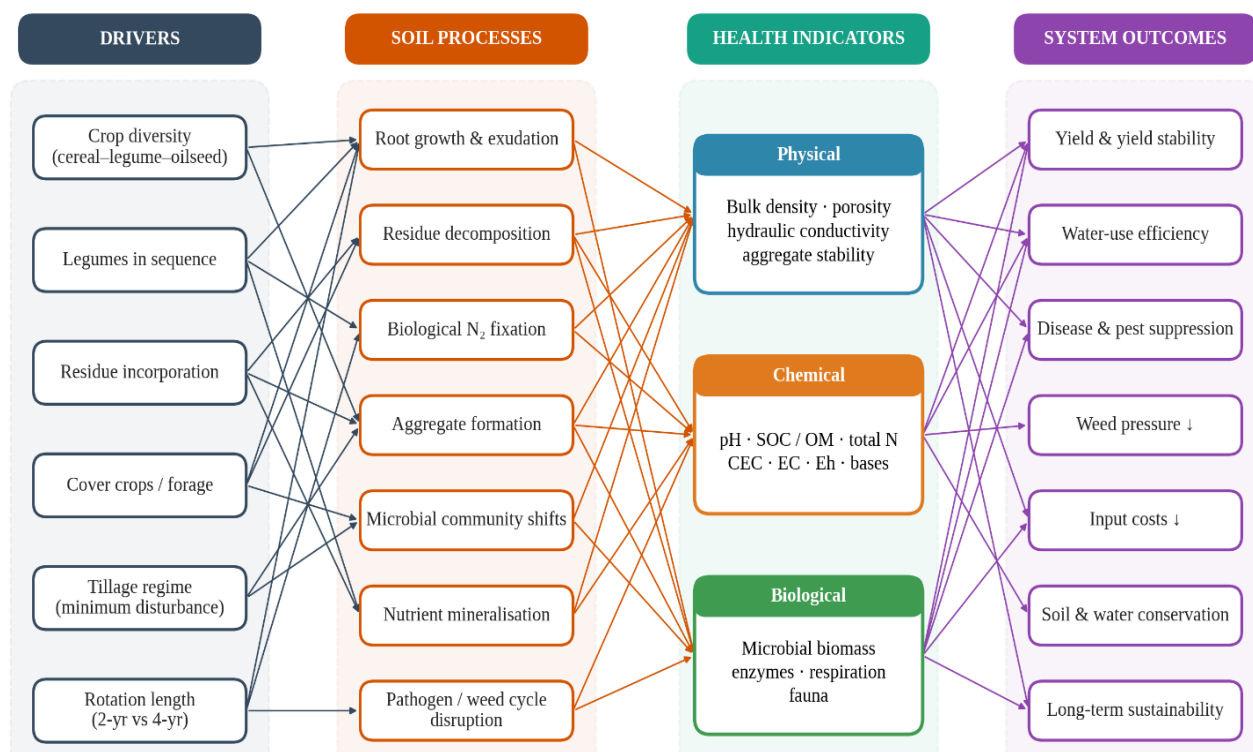


Fig 3: Effect of Crop rotation drivers on soil and overall system productivity

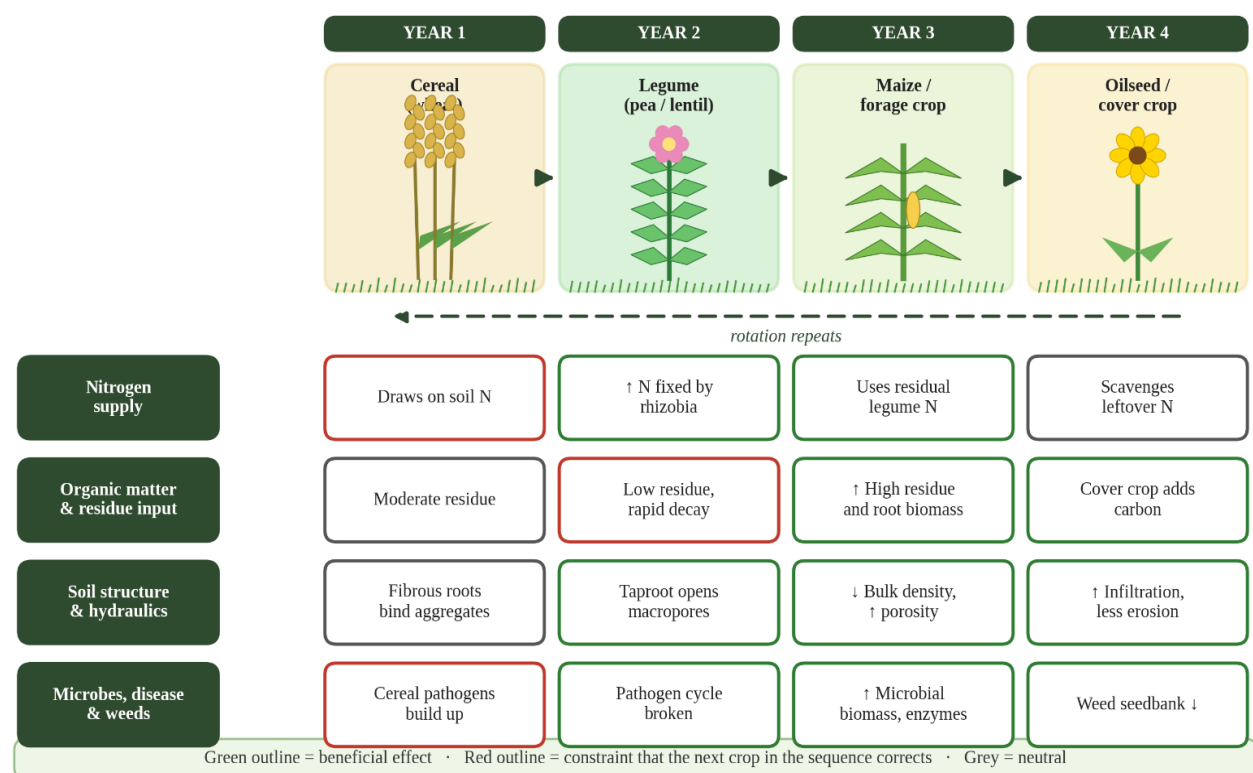


Fig. 4: Effect of crop rotation on soil nutrient, organic matter, hydraulic conductivity and disease management



Fig 5: Crop groups, feeding level and role in rotation. Crops are grouped by family and by how they affect the soil. Each colored card lists the main crops in one group: cereals (gold), legumes (green), brassicas and oilseeds (purple), the potato family (red), roots and alliums (orange), leafy crops and cucurbits (teal), and cover crops and fallow (olive). Each card also gives the group's feeding level (how much it takes from the soil) and its role in the rotation. Legumes make their own nitrogen and leave some in the soil for the next crop. Brassicas and the potato family are heavy feeders and need rich soil. Roots and alliums are light to medium feeders and prefer settled soil. Cereals break disease cycles, leafy crops and cucurbits fit into any gap, and cover crops protect and feed the soil. The golden rules summarize how to order the groups: never repeat a crop family, put legumes before heavy feeders, follow heavy feeders with light ones, alternate cereals and broadleaf crops, and wait 3 to 4 years before pest-prone crops return.

Rotations that include legumes, cover crops or diverse species generally improve soil carbon, nitrogen and cation exchange capacity. Cereal-dominated sequences with carbon-rich straw tend to immobilise N and show weaker nutrient gains. Nutrient responses vary with crop identity, residue quality and management, so rotations should be designed around legumes with high N fixation and residues that decompose at a moderate rate.

Soil pH

Haruna and Nkongolo (2019) reported different pH levels in different cropping systems: continuous corn (6.86), continuous soybean (6.84), corn–soybean rotation (6.74) and soybean–corn rotation (6.85). Similarly, Godsey *et al.* (2007) found that soil OM and pH were significantly influenced by rotation, especially at the soil surface (2.5 cm). In contrast, Xu *et al.* (2002) observed pH variations under wheat–lupin rotation in the 0–10 cm depth increment during a 14-year study. Wei *et al.* (2020) confirmed that soil pH under lentil–wheat–maize (8.42) was lower than under wheat–maize–potato (8.50) during 20 years of rotation. Soil pH under the lentil–wheat–maize system first decreased and then increased with soil depth, but Wei *et al.* (2020) found no significant differences among soil layers. They suggested that the lower water requirement of lentil and wheat stabilised soil pH, whereas pH under wheat–maize–potato increased with depth. Similar findings were reported by Godsey *et al.* (2007). Under wheat–potato–lentil and wheat–flax–pea rotations, soil pH also first decreased and then increased with depth, reaching minimum values of 8.28 and 8.27, respectively, in the 0.1–0.2 m layer (Wei *et al.* 2020). This is consistent with Hong *et al.* (2018), who noted that lentil, pea, flax, wheat and potato have shallow roots that effectively reduce rhizosphere pH by releasing H^+ ions. Wei *et al.* (2020) further observed that soil pH in shallow layers was lower than in deeper layers across four CRs, which was related to the incorporation of aboveground plant residues: these contribute organic acids to the topsoil, which break down before they can acidify the deeper layers, resulting in a relatively higher pH at depth (Chen *et al.* 2016).

In contrast, Degu *et al.* (2019) found that continuous maize resulted in a high pH (5.43), which they attributed to a local ploughing practice (“madager”/“shlshalo”). Exchangeable acidity ranged from 2.02 $cmol_c\ kg^{-1}$ under continuous maize to 4.12 $cmol_c\ kg^{-1}$ under maize–wheat–wheat. Kwiatkowski *et al.* (2020) reported a higher pH in soil under sugar beet (6.5) and the lowest under oat (6.2). Ding *et al.* (2020) showed that soil pH varied over three years of experimentation with garlic rotation, indicating that garlic rotation had greater potential to slow soil alkalisation.

Soil pH responses to crop rotation are real but generally modest, and they depend on the crops involved, the soil depth sampled and local management. Rotations with shallow-rooted crops such as lentil, pea, flax, wheat and potato tended to lower rhizosphere pH through H^+

release, and pH was typically lower in the topsoil than at depth because decomposing surface residues supply organic acids. Differences between rotations at a given depth were often small, whereas management practices such as local ploughing (as with continuous maize) and crop-specific effects (sugar beet versus oat) could shift pH more strongly. Some rotations, such as garlic, may help slow soil alkalisation. Rotation can therefore be used to moderate pH, but its effect should be interpreted alongside soil depth, residue inputs and tillage.

Soil electrical conductivity and redox potential

Bohrerova *et al.* (2004) measured significant differences in redox potential (Eh) among cropping systems in the surface horizon (0–30 cm) of an anaerobic soil, with a lower Eh under sugar beet–barley than under alfalfa–wheat rotation. In addition, soil electrical conductivity (EC) changed significantly during the growing season over three years; in the last two years, for instance, EC decreased with cucumber and increased after garlic (Ding *et al.* 2020). Nocco *et al.* (2019) combined evapotranspiration and soil apparent electrical conductivity (ECa) mapping to identify potential precision irrigation benefits. Variable-rate irrigation based on ECa mapping may lead to higher productivity and water conservation in sweet corn and potato than in field corn. They further deduced that sweet corn and potato had stronger ECa and higher evapotranspiration rates than field corn and, from all six field experiments, recommended precision irrigation based on ECa and evapotranspiration under CR. Apanovich and Lenssen (2018) compared EC across five cropping systems: banana–coffee, coffee-dominant, banana-dominant, annual CR and annual no-CR. EC was highest under the annual rotation system, followed by banana-dominant, banana–coffee, annual no-CR and coffee-dominant systems.

Crop rotation influences soil redox potential and electrical conductivity (EC), but the direction of the effect depends on the crops and the season. Redox potential in the surface horizon was lower under sugar beet–barley than under alfalfa–wheat, and EC shifted within and between growing seasons according to the preceding crop, falling after cucumber and rising after garlic. EC also differed among cropping systems, being highest under annual rotation and lowest under coffee-dominant systems. Because EC mapping reflects differences in crop water use and soil properties, it can support precision irrigation in rotations, with potential gains in productivity and water conservation. Rotation effects on these properties should therefore be interpreted alongside crop identity, sampling time and local management.

Soil cation exchange capacity

Degu *et al.* (2019) reported that cation exchange capacity (CEC) varied from 45.17 to 49.47 $cmol_c\ kg^{-1}$. They noted

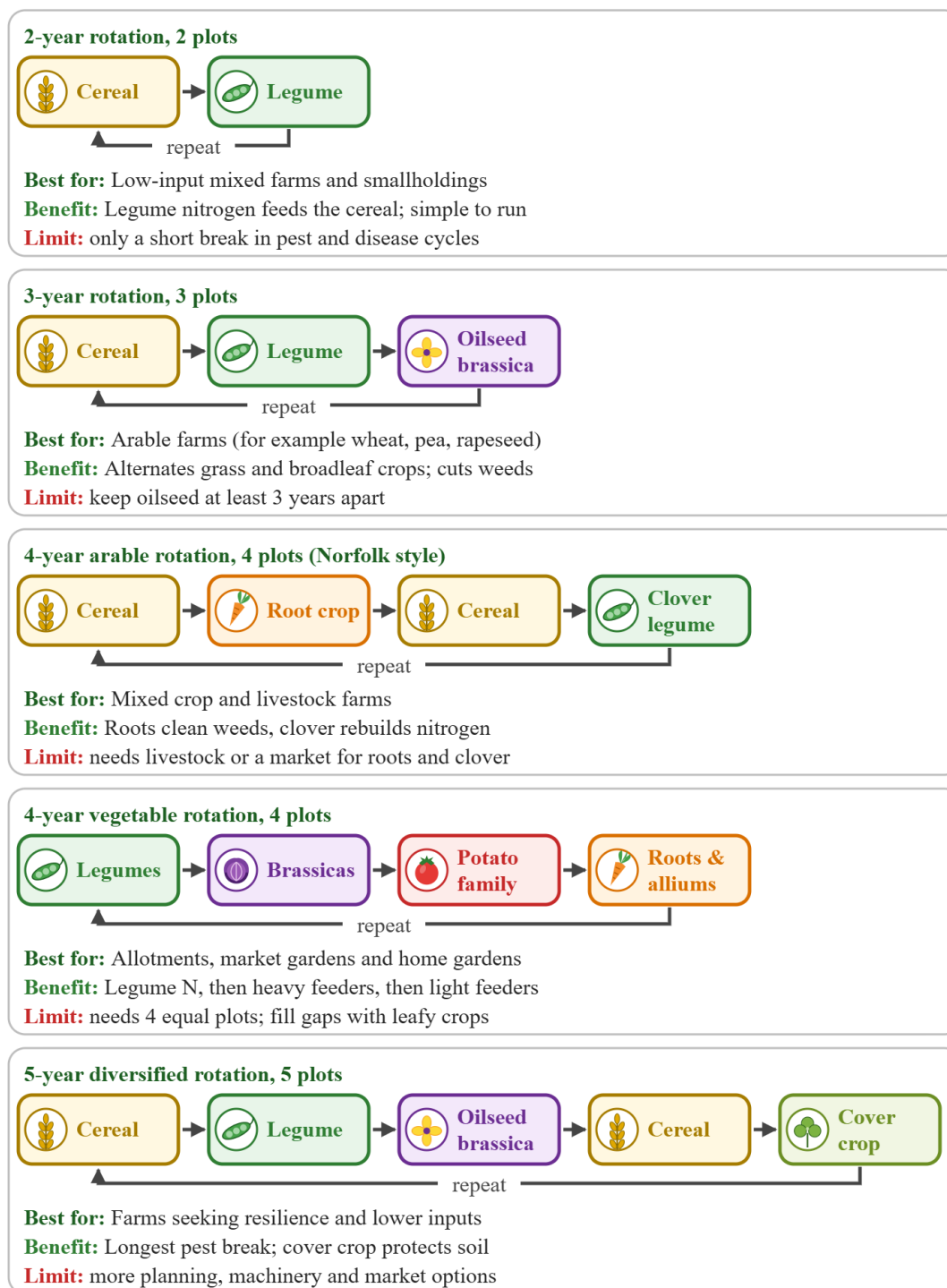


Fig 6: Five crop rotation options, from 2 to 5 years. Each row shows one rotation. The coloured boxes are crop groups: cereals (gold), legumes (green), brassicas and oilseeds (purple), the potato family (red), roots and alliums (orange), and cover crops (olive). Arrows show the order in which the groups follow one another on the same plot, and the return arrow shows that the cycle repeats. The number of plots equals the length of the rotation, so each plot grows a different group every year. The 2-year and 3-year options suit low-input and arable farms. The 4-year arable option (Norfolk style) suits mixed crop and livestock farms. The 4-year vegetable option suits allotments and market gardens, and the 5-year option adds a cover crop for a longer break from pests and disease.

mean CEC values of 44.05 cmol_c kg⁻¹ under maize–wheat–wheat, 48.57 cmol_c kg⁻¹ under maize–wheat–faba bean and 49.47 cmol_c kg⁻¹ under maize–faba bean–pepper. According to Apanovich and Lenssen (2018), CEC was highest in the annual rotation system, followed by banana-dominant, annual no-CR, banana–coffee and coffee-dominant systems.

Rotation design influenced CEC, with higher values under diversified sequences that included legumes or a broader mix of crops, and lower values under cereal-dominated or coffee-dominant systems. Rotations that add legumes and greater crop diversity may therefore improve the soil's capacity to retain nutrients.

Soil exchangeable bases

Exchangeable base cations were generally richer under rotation than under monocropping. Metson (1961) rated Ca²⁺ and Mg²⁺ as high and Na⁺ and K⁺ as moderate to high and found that cropping sequences including rotation held greater quantities of all the exchangeable bases than monocropped land.

Calcium showed the clearest response. Degu *et al.* (2019) recorded exchangeable Ca²⁺ of 10.29 cmol_c kg⁻¹ under continuous maize, compared with 14.22 under maize–wheat–faba bean and 15.28 under maize–faba bean–pepper. They attributed the higher value under maize–wheat–faba bean to the formation of stable complexes between Al³⁺ and organic acids released by faba bean, a process that raises soil acidity and in turn increases exchangeable Ca²⁺ in the soil layer. Magnesium was also higher on rotated land in Metson's (1961) work, although the values reported by Degu *et al.* (2019) were similar across systems, at 6.48 cmol_c kg⁻¹ under continuous maize and 6.00 under maize–wheat–maize.

Potassium and sodium responded differently. Exchangeable K⁺ was greatest under maize–wheat–wheat (2.03 cmol_c kg⁻¹) and least under continuous maize (0.36) (Degu *et al.* 2019), whereas Metson (1961) classed it as moderate. Mean exchangeable Na⁺ was 0.45 cmol_c kg⁻¹ under continuous maize and peaked at 0.68 under maize–pepper–pepper, but it was lower (0.2) in all rotations managed with conservation practices than on land without them (Degu *et al.* 2019).

Taken together, these results suggest that rotation, and especially legume inclusion, improves the base cation status of soil. Degu *et al.* (2019) therefore advised rotating maize with other crops, particularly legumes and vegetables, to reduce heavy reliance on mineral fertilization. (Degu *et al.* 2019).

Rotation generally increased exchangeable base cations relative to monocropping, although the response varied by cation and crop sequence. Calcium was higher under rotations that included faba bean, likely because organic acids from this crop form stable complexes with Al³⁺, whereas magnesium, potassium and sodium showed more variable responses. Conservation practices were

associated with lower exchangeable sodium. Maize fields should therefore be rotated with other crops, particularly legumes and vegetables, to improve base cation status and reduce reliance on mineral fertilisation.

CROP ROTATION AND SOIL BIOLOGICAL CHARACTERISTICS

Soil enzymes

Protease and dehydrogenase activities are higher under CR than under monoculture (Balota *et al.* 2004; Gianfreda *et al.* 2005). Kwiatkowski *et al.* (2020) reported that land rotated with red clover and sugar beet had the most beneficial effect on soil enzyme activity, followed by oat. Balota *et al.* (2004) further found that amylase activity at 5–10 and 10–20 cm depth was 20% higher under maize–wheat than under soybean–wheat and 11% higher than under cotton–wheat rotation. Arylsulfatase activity was influenced at 5–10 cm: maize–wheat had 37% and 27% higher activity than sugar beet–wheat and cotton–wheat rotations, respectively. Moreover, acid phosphatase activity was 6% and 10% higher under maize–wheat than under sugar beet–wheat and cotton–wheat, respectively, whereas alkaline phosphatase activity was lower under cotton–wheat than under the other rotations.

Borase *et al.* (2020) found that pigeon pea–wheat, maize–wheat–mung bean and maize–wheat–maize–chickpea had higher activities of protease (5–51%), dehydrogenase (52–79%), alkaline phosphatase (20–80%), β-glucosidase (9–16%) and arylsulfatase (16–35%) than maize–wheat. Ding *et al.* (2020) reported that soil invertase and catalase activities increased with onion and garlic rotation.

Soil enzyme activities were generally higher under diversified rotations than under monoculture or simple two-crop systems. Activities of protease, dehydrogenase and phosphatases increased where legumes, cover crops or alliums were included, and rotations with red clover and sugar beet had particularly beneficial effects. The response varied with crop identity and soil depth, however, as maize–wheat gave higher amylase, arylsulfatase and acid phosphatase activity than some other two-crop sequences. Rotations that add legumes and a broader range of crops can therefore enhance biological activity and nutrient cycling in soil.

Rotation generally enhances soil enzyme activity, particularly where legumes, cover crops or alliums are included. The magnitude of the response varies with crop identity and soil depth, so rotations that combine legumes with a broader range of crops are likely to improve microbial function and nutrient cycling most effectively.

Soil microbial communities

Microbes can protect hosts from disease, but the

Table 1: Quantitative effects of crop rotation on soil properties, weeds, disease and system productivity in the reviewed studies

Parameter	Rotation (treatment)	Comparator	Reported values	Δ (%)	Reference
Soil water content	Lentil–wheat–maize	Wheat–maize–potato	9.81 vs 8.43%	+16.4†	Wei <i>et al.</i> 2020
Bulk density	Maize–soybean	Continuous maize	1.29 vs 1.40 g cm ⁻³	-7.9†	Nebo <i>et al.</i> 2020
Bulk density	Lentil–wheat–maize	Wheat–maize–potato	1.19 vs 1.16 Mg m ⁻³	+2.6†	Wei <i>et al.</i> 2020
Macroporosity (X-ray CT)	4-yr maize–soybean–oat–winter wheat	2-yr maize–soybean	↑ pore number, coarse mesopores (226–1000 μ m), macropores (>1000 μ m)	—	Singh <i>et al.</i> 2020
Soil organic carbon	Pigeon pea–wheat; maize–wheat–mung bean	Maize–wheat	—	+22; +12	Borase <i>et al.</i> 2020
Soil organic carbon	4-yr maize–soybean–oat–winter wheat	2-yr maize–soybean	—	+16	Singh <i>et al.</i> 2020
Soil organic carbon	Maize–pepper–pepper	Continuous maize	2.97 vs 2.63%	+12.9†	Degu <i>et al.</i> 2019
Soil organic carbon	Corn–soybean (short)	Continuous corn	Lower (not quantified)	↓	Coulter <i>et al.</i> 2009; Benjamin <i>et al.</i> 2010
Soil organic carbon	20-yr lentil–wheat–maize	Wheat–maize–potato	6.81 vs 6.91 g kg ⁻¹	-1.4† (n.s.)	Wei <i>et al.</i> 2020
Total nitrogen	4-yr maize–soybean–oat–winter wheat	2-yr maize–soybean	—	+14	Singh <i>et al.</i> 2020
Total nitrogen	Soybean–lentil; soybean–pea	Soybean–wheat	—	+19; +21	Bhattacharyya <i>et al.</i> 2009
Exchangeable Ca ²⁺	Maize–faba bean–pepper	Continuous maize	15.28 vs 10.29 cmolc kg ⁻¹	+48.5†	Degu <i>et al.</i> 2019
Exchangeable K ⁺	Maize–wheat–wheat	Continuous maize	2.03 vs 0.36 cmolc kg ⁻¹	+464†	Degu <i>et al.</i> 2019
Cation exchange capacity	Maize–faba bean–pepper	Maize–wheat–wheat	49.47 vs 44.05 cmolc kg ⁻¹	+12.3†	Degu <i>et al.</i> 2019
Available P	Maize–wheat–wheat	Continuous maize	6.09 vs 10.21 ppm	-40.4†	Degu <i>et al.</i> 2019
Dehydrogenase	Pigeon pea–wheat; maize–wheat–mung bean; maize–wheat–maize–chickpea	Maize–wheat	—	+52 to +79	Borase <i>et al.</i> 2020
Protease	As above	Maize–wheat	—	+5 to +51	Borase <i>et al.</i> 2020
Alkaline phosphatase				+20 to +80	
β -Glucosidase				+9 to +16	
Arylsulfatase				+16 to +35	
Soil respiration	Pigeon pea–wheat	Maize–wheat	—	+15	Borase <i>et al.</i> 2020
Disease-suppressive pmD gene	Corn–soybean–wheat + two cover crops	Monoculture	—	+9	Peralta <i>et al.</i> 2018
Weed cover	6-yr corn–soybean–wheat–hay	2-yr corn–soybean	20 vs 40%	-50†	Teasdale <i>et al.</i> 2018
Weed seedbank variance	Preceding three-year crop sequence	—	> 80% explained	—	Bohan <i>et al.</i> 2011
Herbicide use	Cereal–break–crop rotation with targeted weed control	Standard herbicide programme	—	-50	Jordan and Donaldson 1996
Potato soil-borne disease	Rapeseed in potato rotation	Without rapeseed	Incidence ↓ 10–52%	-10 to -52	Bernard <i>et al.</i> 2014
Oilseed rape yield	Two-year break	Continuous rape	3.36 vs 2.79 t ha ⁻¹	+20.4†	Stobart 2011
System robustness	Most diverse 3-yr chickpea rotations	Less diverse rotations	—	+14	Li <i>et al.</i> 2019

Δ , relative change in the rotation (treatment) compared with the comparator. † Calculated from the reported means as (treatment – comparator) / comparator $\times$ 100; all other values are as reported in the source study. Semicolons separate values for the treatments listed in the same order. n.s., not significant; †/↓, increase/decrease; —, not reported.

mechanisms underlying their function in complex agroecosystems remain unresolved.

For instance, Zuber *et al.* (2018) found no differences in microbial activities among continuous soybean, corn–soybean and corn–soybean–wheat rotations. In another study, Wright *et al.* (2015) investigated six CRs (three potato-focused and three onion-focused) in a 10-year trial. Soils from the three potato-focused rotations had the same microbial biomass but different microbial activity

parameters. Peralta *et al.* (2018) reported that CR increases microbial diversity and disease-suppressive capacity, either by influencing soil bacterial composition and plant diversity or by enhancing disease-suppressive microorganisms (Table 1).

Rotation effects on soil microbial communities are inconsistent and depend on the cropping system and the microbial parameter measured. Even so, diversified rotations can enhance microbial diversity and disease

suppression, although the underlying mechanisms need further investigation.

Overall, rotation effects on soil microbial communities are inconsistent and depend on both the cropping system and the microbial parameter measured. Diversified rotations nonetheless appear to enhance microbial diversity and disease suppression, although the underlying mechanisms require further investigation.

CROP ROTATION AND SYSTEM PRODUCTIVITY

Crop yield

Yield is probably the outcome of rotation that producers and researchers care about most. It is also a system-level result, since it reflects the combined state of the soil's physical, chemical and biological condition. As climate change adds pressure to farming systems, a further benefit of diverse rotations is drawing interest: they can make production more stable and better able to absorb shocks. Several studies illustrate this. Stobart (2011) compared oilseed rape grown in different sequences and found a clear penalty for repeating the crop. Rape sown on land that had never carried it produced 3.9 t ha⁻¹, while continuous rape managed just 2.79 t ha⁻¹. Growing it every second year gave 3.13 t ha⁻¹, and leaving a two-year gap raised this to 3.36 t ha⁻¹. In southern Sweden, Persson *et al.* (2008) followed arable rotations at three sites for 21 years, including a two-year ley phase of either pure grass or a grass–legume mix. At one of the sites, winter wheat did better when the ley

contained legumes. Wright *et al.* (2017) worked with potato and onion systems that ranged from monocultures to alternating potato–onion sequences and four-year rotations. Potatoes yielded more when they did not follow potatoes, and the four-crop rotation gave the best potato yield. Onions performed worst under continuous onion production. More recently, Li *et al.* (2019) ran three-year rotations through two full cycles, all centered on chickpea. The treatments paired chickpea with three different crops, with only one other crop, or grew it continuously. The most diverse rotations coped best with both abiotic and biotic stress, kept productivity steadier from one cycle to the next, and raised system robustness by 14%. Continuous chickpea, by contrast, ended in complete crop failure. So, across crops and environments, diversified and longer rotations raised yield and improved its stability, whereas continuous cropping consistently incurred yield penalties and, in the extreme case, crop failure.

Weed management

Crop rotation was widely regarded as an effective weed management tool even at the onset of the herbicide era, and subsequent research has largely supported this view. In an 18-year experiment comparing a two-year corn-soybean

rotation, a three-year corn-soybean-wheat rotation and a six-year corn-soybean-wheat-hay rotation, mean weed cover declined with increasing rotation length, at 40%, 27% and 20%, respectively (Teasdale *et al.* 2018).

Rotation also structures weed communities in systems where herbicides are applied. Using national-scale arable datasets from the UK, Smith *et al.* (2008) reported that the composition of weed species and functional types was strongly associated with the current crop, with variation in weed assemblages between crops exceeding that within crops. They further demonstrated that contemporary weed assemblages could be predicted from the crops grown in the preceding three years, with sowing season, crop type and the weed species targeted by herbicide application identified as the principal determinants. In a factorial investigation of crop sequence, cultivar, sowing date and nitrogen supply, Froud-Williams *et al.* (1996) found that weed biomass was influenced most strongly by the two preceding crops and their interaction. For example, weed biomass in the second rotational year was greater in rape than in wheat, and greater in wheat-rape than in wheat-wheat sequences. Consistent with these findings, Bohan *et al.* (2011) analyzed farmland seedbank datasets and found that the crop sequence of the previous three years accounted for more than 80% of the variation in weed seedbanks.

Rotation can also be deployed strategically to mitigate weed problems associated with other management practices. Non-inversion tillage frequently promotes the proliferation of grass weeds. Jordan and Donaldson (1996) limited this build-up through an active rotational strategy in which cereals were alternated with break crops. Grass weeds were targeted in broad-leaved crops and broadleaf weeds in cereals, using herbicides supplemented with mechanical control. This approach achieved effective weed control while reducing herbicide use by 50% relative to a standard herbicide program. A similar approach was adopted by Jordan and Hutchinson (1996) within the LIFE project (less-intensive integrated production systems). Specific weeds were targeted in crops that permitted the use of the most effective herbicides, whereas the same weeds were tolerated in crops with fewer effective herbicide options. This improved weed management while reducing herbicide inputs. The authors also reported that the sowing date of the current crop influenced weed biomass, whereas wheat cultivar had no detectable effect.

In conclusion, rotation length and crop sequence are major determinants of weed abundance and community composition, and designing sequences around weed and herbicide options can improve control with lower herbicide inputs.

Disease management

Altering the crop sequence is among the oldest cultural practices for managing plant disease, and it remains the most effective means of controlling take-all of cereals,

caused by *Gaeumannomyces graminis* var. *tritici* (Kwak and Weller 2013). Chemical control of soil-borne pathogens is generally impractical, because the soil matrix physically shields the pathogens and can bind or degrade agrichemicals before they act. Rotation therefore remains one of the most effective strategies for managing soil-borne pests.

Evidence from potato and onion systems supports this. Over four years, Wright *et al.* (2017) observed that black scurf of potato (*Rhizoctonia solani*) was most severe in potato and onion monocultures and lower in potato-onion rotations. Read (1996) reported a comparable result, with double cropping of potato increasing disease symptoms caused by *R. solani*. Incorporating rapeseed (*Brassica napus*) into a potato rotation reduced the incidence of *R. solani*, silver scurf (*Helminthosporium solani*) and common scab (*Streptomyces scabiei*) by 10-52% in at least one year at both experimental sites (Bernard *et al.* 2014). On the basis of these outcomes, Wright *et al.* (2015) recommended four-year rotations in intensive onion and potato production to limit soil-borne disease and sustain yield.

CR is the most important practice for reducing the carry-over of biotrophic pathogens, which require living hosts and cannot survive saprophytically (Peters *et al.* 2003). It is less effective against pathogens such as *Spongospora subterranea*, *Sclerotinia* spp., *Pythium* spp. and *Fusarium* spp., which have long-term survival structures and broad host ranges (Krupinsky *et al.* 2002), and against pathogens with high population densities (Peters *et al.* 2003). However, some pathogens, such as *Pectobacterium carotovorum*, can be effectively reduced through CR (Hopkins *et al.* 2004).

Murphy (1997) reported that corn grown in rotation with potato gave excellent control of Verticillium wilt, a soil-borne disease that drastically reduces potato yield. Schwartz (2012) indicated that CR helps to overcome pathogen-infested soil and suggested that onion should be grown in a field no more than once every five years. He recommended barley as an alternative crop to onion, which not only improves organic matter but also reduces the risk of Fusarium basal rot and pink root. It is noteworthy that infestation of onion with *Phoma terrestris* and *Fusarium oxysporum* f. sp. *cepa* was reduced by rotating with non-susceptible crops for four years (Havey 1995; Sumner 1995). Peralta *et al.* (2018) determined that soil diversity under monoculture was 4% higher than under diverse CR (corn-soybean-wheat plus two cover crops). According to their findings, crop diversity increased the pmD gene (a disease-suppressive functional group) under diverse rotation by about 9% compared with monoculture. Lyu *et al.* (2020) found that fungal richness in Chinese cabbage rotation was significantly lower than in other CRs, while fungal diversity was highest under tomato cropping. They confirmed that celery rotation increased fungal richness and diversity. In contrast, Ding *et al.* (2020) found that fungal activity increased dramatically with garlic CR in an onion field (Fig. 5–6).

In summary, Rotation suppresses soil-borne disease

most reliably for pathogens that depend on living hosts, and it can also enrich disease-suppressive microbial functions. Its effect is weaker against pathogens with persistent survival structures or wide host ranges, so rotation should be designed around the specific pathogens and crops involved.

CONCLUSION

Crop rotation influences soil health across its physical, chemical and biological dimensions. Diversified rotations that include legumes, forage crops or cereals generally reduced bulk density, improved porosity, hydraulic conductivity and water retention, and increased soil organic carbon, nitrogen and other nutrients, although responses varied among soils, rotations and durations: short-term trials found little effect on macroporosity, and some studies found no difference in organic carbon or microbial activity. Legume-based rotations were associated with higher N availability, exchangeable bases and enzyme activities. Longer, more diverse rotations also suppressed weeds (average weed cover of 20% under a six-year rotation compared with 40% under a two-year rotation) and soil-borne diseases, and they improved the stability of crop yields (a 14% increase in system robustness). Future research should focus on long-term, multi-site experiments that compare rotation sequences under contrasting soils and climates, and on resolving the microbial mechanisms through which rotations suppress disease and regulate nutrient cycling.

Crop rotation influences soil health across its physical, chemical and biological dimensions. Diversified rotations that include legumes, forage crops or cereals generally reduced bulk density, improved porosity, hydraulic conductivity and water retention, and increased soil organic carbon, nitrogen and other nutrients, although responses varied among soils, rotations and durations: short-term trials found little effect on macroporosity, and some studies found no difference in organic carbon or microbial activity. Legume-based rotations were associated with higher N availability, exchangeable bases and enzyme activities. Longer, more diverse rotations also suppressed weeds (average weed cover of 20% under a six-year rotation compared with 40% under a two-year rotation) and soil-borne diseases, and they improved the stability of crop yields (a 14% increase in system robustness). Future research should focus on long-term, multi-site experiments that compare rotation sequences under contrasting soils and climates, and on resolving the microbial mechanisms through which rotations suppress disease and regulate nutrient cycling.

NOVELTY STATEMENT

- Integrates the effects of crop rotation on soil physical, chemical and biological properties and on system productivity in a single review

- Compares contrasting rotation sequences using quantitative values reported from long-term field studies
- Identifies legume- and diversity-based rotations as consistently beneficial for soil organic carbon, nitrogen and enzyme activity
- Links rotation-driven weed and disease suppression to reduced herbicide use and greater yield stability
- Highlights inconsistent responses and unresolved microbial mechanisms as priorities for future

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AUTHOR CONTRIBUTIONS

TA conceptualized the review and prepared the original draft. MN contributed to literature collection, analysis, and interpretation. YR contributed to critical review, editing, and final approval of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The author declares no conflict of interest.

DATA AVAILABILITY

No new data were generated in this review. All data discussed are available in the cited publications.

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Affordable and Resilient Housing for Sustainable Urban and Economic Development: A Comparative Policy Analysis of Saudi Vision 2030, the UN Sustainable Development Goals, and Pakistan's National Housing Framework

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ABSTRACT

Background: More than 1.6 billion people around the world are living without safe and decent housing, which is one of the greatest challenges in the pursuit of sustainable urban development in the twenty first century.

Objective: This paper aims to provide a policy comparison of three key policies, Vision 2030 housing agenda by Saudi Arabia, the United Nations Sustainable Development Goals (SDGs) relevant to housing and urbanisation (SDGs 1, 8, 9, 11 and 13) and the National Housing and Urbanisation Policy (NHUP) of Pakistan.

Methodology: The study identifies the critical convergences, structural gaps, and contextual divergences between these systems through a systematic document analysis, multi-criteria comparative matrices and structured case study review. It presents a novel conceptual framework called the Saudi-Pakistan Affordable and Resilient Housing Framework (SPARH), that incorporates four strategic elements: Housing affordability and financial inclusion, Climate resilience and Disaster risk reduction, Smart urban infrastructure, and Economic development linkages.

Results: Saudi Vision 2030 is particularly effective at institutional transformation and finance innovation, yet the Pakistan plan does not explicitly consider on-the-ground equity issues, and both plans fail to include planning and economic linkages between sectors and across sectors that incorporate climate resilience.

Conclusion: The SPARH policy framework provides a policy blueprint which can be transferred to other emerging economies that are facing rapid urbanisation, climate vulnerability and fiscal constraints. The paper ends with policy recommendations to advance the global agenda of affordable housing through bilateral cooperation, international financing mechanisms and governance innovations.

INTRODUCTION

Urbanization is changing the way people live and work in the twenty- century. The United Nations says that 68% of people around the world will live in cities by 2050. This means 2.5 billion more people will live in cities. Most of these city dwellers will be in Asia and Africa. This change is making a problem even worse. The World Bank says that than 1.6 billion people do not have enough housing. The biggest problems are in South Asia, Sub-Saharan Africa and

parts of the Middle East. The problem is not about having enough houses. It is also about making sure the houses are affordable, safe and can handle weather changes. It is also about having roads, water and electricity. It is about making sure cities grow in a way that is good for the planet.

Two places where this problem is very important are the Kingdom of Saudi Arabia and the Islamic Republic of Pakistan. Even though these two countries have kinds of economies, they both face serious problems with housing. Saudi Arabia is a country that makes a lot of money from

oil. It is changing its economy. It still has a problem with not enough houses. The country has a lot of people and building houses is expensive. Also, the way the economy has worked in the past has not helped private companies build houses. Pakistan is a country where people are not as rich. It has a lot of people who are moving to cities. There are not enough houses. There are problems too like the risk of earthquakes and floods. The country also does not have roads, water and electricity.

Both countries have plans to solve their housing problems. Saudi Arabia has a plan called Vision 2030. This plan says housing is very important. The goal is to get more people to own their homes. The plan has ideas about how to do this. Pakistan has a plan called the National Housing and Urbanization Policy. Recently there is also the Naya Pakistan Housing Program. These plans try to build houses by working with private companies and using new technology. It is hard to make these plans work. These efforts happen while the world is trying to follow the United Nations 2030 Agenda for Sustainable Development. This agenda has goals about ending poverty, making sure people have jobs, making sure cities are safe and fighting climate change. These goals are important for housing. It is hard to make these goals into real policies for each country. This paper has three ideas. First, it looks at how the housing policies of Saudi Arabia, the United Nations goals and the policies of Pakistan're similar and different. It uses a way of looking at these policies. Second it finds where these policies are not working well and where they could help each other. It suggests ways to learn from each other. Third it introduces an idea called the Saudi Pakistan Affordable and Resilient Housing Framework. This is a way to solve housing problems in countries that are growing quickly.

The rest of the paper is divided into sections. First, it looks at what other people have written about safe housing. Then it explains how the research was done and what the big problems are, around the world. Then it looks at the policies of Saudi Arabia, the United Nations and Pakistan. After that it compares them. Look at examples. Then it talks about what it found, explains the idea and gives suggestions. Finally, it ends with the things learned and what could be studied next.

BACKGROUND OF THE STUDY

Affordable housing: definitions and debates

The concept of housing affordability has evolved considerably over the past four decades. The conventional threshold that housing is affordable when housing costs do not exceed 30% of household income has been challenged by scholars as insufficiently sensitive to the full cost of housing location, including transport, utilities, and opportunity costs (Stone 2006; Hulchanski 1995). A 'residual income' approach, which evaluates whether households can meet non-housing needs after paying for

shelter, has gained traction as a more accurate measure of housing stress (Stone 2006). More recently, scholars have called for a multi-dimensional definition that incorporates access to services, tenure security, physical quality, and community integration (Wetzstein 2017).

In the Global South, affordability is inseparable from informality. Approximately 1.1 billion people globally live in slums or informal settlements, where housing is technically 'affordable' by price but deeply unaffordable in terms of inadequate services, insecurity of tenure, and climate exposure (UN-Habitat 2022). Angel *et al.* (2011) and Buckley *et al.* (2016) argued that the enabling approach—shifting governments from housing providers to market enablers—has failed to adequately address the housing needs of the lowest-income quintiles, particularly in rapidly urbanising societies. The debate continues between supply-side interventions (land release, regulatory simplification, construction technology), demand-side interventions (subsidies, housing finance, vouchers), and integrated strategies that address both simultaneously.

Urban resilience and housing

The ability of cities and communities to resist, adapt to, and recover from shocks and stresses is a key concept in urban planning since the early 2000s (Davoudi 2012, Meerow *et al.* 2016). Resilience in housing includes structural resistance to natural hazards (earthquake, flood, cyclone) and adaptation to the climate (heat resilience, water efficiency), as well as socioeconomic resilience (tenure security, community networks, livelihood diversity). The Sendai Framework for Disaster Risk Reduction 2015 2030 explicitly mentions housing as a disaster risk and that informal settlements are highly susceptible to losses due to hazard risks (UNDRR 2015). There has been inconsistent implementation of resilience into affordable housing policy. There are also important differences in the sophistication of building codes, risk-informed land use planning and insurance systems between high-income and low- and middle-income countries, with the latter often having to choose between affordability and resilience (Birkmann *et al.* 2016; Satterthwaite *et al.* 2020). Recent scholarship has focused on the cost premium for resilient construction, which is expected to be 3-10% for seismic or flood resistance, and how disaster losses over the building's life cycle can make it economically viable in the first place, before it becomes technically feasible (World Bank 2019).

Housing, economic development, and smart urbanism

The relationship between housing investment and economic development is well-established in the literature. Housing construction is a labour-intensive sector with significant backward linkages to materials, services, and finance sectors, making it a potential engine of inclusive economic growth (De Soto 2000; Buckley and Kalarickal 2006). In

Saudi Arabia, the housing sector is viewed as a key economic diversification vehicle in the Vision 2030 framework, expected to contribute to GDP diversification, private sector employment, and domestic capital markets (Vision 2030 2016). In Pakistan, housing has been positioned similarly as a poverty alleviation tool with employment multiplier effects, particularly through the NPHP (Government of Pakistan 2019).

Smart urbanism—the application of digital technologies, data analytics, and network infrastructure to urban management—is increasingly intersecting with affordable housing policy. Smart building technologies can reduce operational costs for residents, while data-driven urban planning can improve site selection, resource allocation, and monitoring (Yigitcanlar *et al.* 2019). However, critics caution that the smart city paradigm often privileges technology adoption without adequate attention to equity, community participation, and the needs of low-income urban residents (Hollands 2008; March and Ribera-Fumaz 2016). The literature thus calls for ‘inclusive smart urbanism’ that centres affordability and social equity alongside efficiency and innovation.

Comparative housing policy studies

The comparative housing policy literature has a rich tradition of cross-national analysis, from Kemeny’s (1992) work on the distinction between unitary and dualist rental markets, to Whitehead and Scanlon’s (2007) comparative studies of social housing in Europe, and more recent efforts to compare housing policies across the Global South (Pugh 2001; Rolnik 2013). Within the Middle East and South Asian context, comparative housing scholarship is thinner, partly reflecting a historical focus on shelter in international development circles rather than integrated economic and urban development frameworks. This paper seeks to fill a gap in the literature by systematically comparing Saudi and Pakistani housing frameworks with global normative standards, and by proposing an original integrated framework for cross-national policy learning.

METHODOLOGY

This study employs a qualitative comparative policy analysis methodology, triangulated with structured document review, multi-criteria policy matrix construction, and illustrative case study analysis. The research design is consistent with the interpretive policy analysis tradition (Fischer 2003; Yanow 1996), adapted to accommodate a cross-national comparative framework.

Data sources and document analysis

Key primary policy documents are: Saudi Vision 2030 Housing Programme documentation; National Transformation Programme 2020 (Saudi Arabia); NHUP

2021-2025 (Pakistan); NPHP policy guidelines; UN SDGs monitoring tools and Voluntary National Review for each country; UN-Habitat Global State of Housing; World Bank housing sector analysis; and OECD housing policy reviews. Literature secondary sources were systematically sourced from Scopus, Web of Science, and Google Scholar databases through search terms such as ‘affordable housing,’ ‘resilient housing,’ ‘Saudi housing policy,’ ‘Pakistan housing policy,’ ‘UN SDG 11,’ among others.

Comparative policy matrix

A six-dimension comparative policy matrix was constructed to systematically evaluate the three frameworks (Saudi Vision 2030, UN SDGs, Pakistan NHUP) across the following analytical dimensions: (i) affordability targets and mechanisms; (ii) housing finance and subsidy structures; (iii) climate resilience and disaster risk reduction; (iv) smart urban infrastructure integration; (v) economic development linkages; and (vi) governance and implementation architecture. Each dimension was evaluated using a four-point scale (Absent / Weak / Moderate / Strong) calibrated against international best practice standards drawn from the literature.

Case study selection

Three national and subnational case studies were selected for in-depth analysis using purposive sampling: (i) Saudi Arabia’s National Housing Company (NHC) new town development programs; (ii) Pakistan’s Naya Pakistan Housing Programme pilot projects in Islamabad and Khyber Pakhtunkhwa (KPK); and (iii) comparative international examples including Singapore’s Housing and Development Board (HDB) and South Africa’s Breaking New Ground housing programme, selected for their relevance to the affordability-resilience-economic development nexus. Case data were gathered from project reports, grey literature, media sources, and, where available, academic evaluations.

Saudi-Pakistan Affordable and Resilient Housing (SPARH) framework development

The SPARH framework was developed through a three-stage process: (i) gap analysis from the comparative matrix; (ii) synthesis of international best practice from the case studies and literature; and (iii) conceptual integration using systems thinking to identify four strategic pillars and their inter-linkages. The framework was structured to be applicable across both Saudi and Pakistani contexts while remaining adaptable to other emerging economy settings.

GLOBAL HOUSING CHALLENGES

There are multiple global housing issues relating to quantity, quality, vulnerability to climate change, and affordability.

The quantity is very high with the UN-Habitat (2023b) estimating that we will need to increase the number of units we build globally by 96,000 each day until 2030; equalling around 2 billion new units. These issues will heavily impact South Asia, accounting for 35% of the global requirement, and Sub-Saharan Africa (25%). With secondary issues affecting Southeast Asia and portions of the Middle East and North Africa (MENA) regions. There is an expected need for 1.5 million new units to be constructed within urban areas over Saudi Arabia and the MENA region every decade (World Bank 2022).

The quality of housing is also an issue. The World Health Organisation estimate that over 3.5 billion people reside in housing not up to minimum requirements with regards to structure, sanitation, and ventilation, or are overcrowded (WHO 2018). Informal settlements with vulnerable housing to climate change have grown due to them often being built on flood plains, hills, and other undesirable land. Over 1 billion people live in these settlements within developing countries. Climate change has increased the risk that housing faces. The Intergovernmental Panel on Climate Change (IPCC) has estimated that housing will face much higher costs associated with damage and displacement from increased sea levels, severe storms, high temperatures, and changes in rainfall patterns in coming decades (IPCC 2022). For example, Pakistan had major flooding in 2022 which caused over 1.7 million homes to be damaged/destroyed. The cost of damages to housing was estimated to be over USD 5.6 billion, showing how poverty, inadequate housing, and climate change can cause issues (Pakistan Federal Flood Commission 2022).

Economic exclusion from formal housing markets affects the majority of urban residents in low- and middle-income countries. Formal housing finance systems typically require stable incomes, collateral, and credit histories that exclude informal-sector workers, who constitute the majority of the workforce in Pakistan (approximately 72%) and a significant portion of Saudi Arabia's migrant workforce. The result is a 'missing middle' in housing finance: households too affluent for government-subsidised housing but too poor for formal market products, driving the growth of informal settlements (Datta and Jones 2001; Mercer 2020). Selected indicators for each of these dimensions are summarised in Table 1.

SAUDI VISION 2030 HOUSING POLICIES

Overview and policy architecture

Saudi Vision 2030 is the biggest restructuring of the Saudi Arabian state since the oil boom era, announced by Crown Prince Mohammed bin Salman in April 2016. In this national transformation agenda, housing is a focal point, which is set out as one of 13 Vision Realisation Programs, with a Vision 2030 target of achieving homeownership to increase from 47% (2016 baseline) to 70% by 2030 (Housing Programme

2018). Major restructuring of institutional frameworks for housing delivery under Vision 2030. The Ministry of Housing was bolstered and enhanced in its coordinating capacity. The National Housing Company (NHC) is of joint-stock company which is responsible for large-scale housing development and public-private partnership. The Real Estate Development Fund (REDF) was reorganized as the main form of mortgage loan facilitation and subsidy, providing subsidized loans to eligible Saudi nationals. The Real Estate General Authority (REGA) was created to control the real estate industry, increase transparency and end land hoarding.

Affordability mechanisms

The cornerstone of Saudi Vision 2030's affordability strategy is the Sakani programme, launched in 2017, which integrates housing land allocations, subsidised mortgage products, and ready-to-build infrastructure. By 2023, the Sakani programme had provided over 700,000 housing solutions (a combination of plots, apartments, and mortgage subsidies), substantially exceeding initial targets (NHC 2023). The REDF offers mortgage support products including profit-rate subsidies, down-payment assistance, and guarantees to commercial banks, making formal homeownership accessible to first-time buyers in the middle- and lower-middle-income segments.

Land policy has been an important issue for making housing affordable. Urban land markets have traditionally been dominated by vacant land speculation in Saudi Arabia. To increase land supply and tackle land speculation, the White Land Tax was introduced in 2017 under Vision 2030. This tax is applied to vacant land over a certain minimum size in urban areas. Initial evidence suggests that it has been somewhat successful at increasing land supply however there have also been issues with implementation and avoidance (Al-Surf and Bharat 2021).

Construction technology and quality standards

Saudi Vision 2030 has explicitly promoted industrialized and modular construction technologies as mechanisms to reduce construction costs, improve quality, and accelerate delivery. The NHC has piloted prefabricated construction systems in several large-scale developments, and a National Building Code revision process has been ongoing to incorporate energy efficiency, structural resilience, and smart building standards.

The government has also promoted the adoption of Building Information Modelling (BIM) for large housing projects, aligning with global trends in construction digitization. However, climate adaptation in building standards remains an underdeveloped area. Saudi Arabia's severe climate (with peak summer temperatures exceeding 45°C in interior cities) creates significant building performance requirements for cooling energy efficiency and heat-island management, yet systematic integration of

passive cooling design and urban heat island mitigation into national housing program remains limited (Alshehri 2020).

Gaps and critiques

Despite Vision 2030 housing having achieved some successes there have also been substantial criticisms. Scholars of social equity have identified that the Sakani programme is very focused on providing housing for Saudi Nationals within the formal sector. This leaves a huge amount of low income workers, such as many Saudi females who have recently entered the workforce, without housing (Alqahtani and Saber 2022). Migrant workers make up around 38% of the overall population of Saudi Arabia and play a key role in the construction sector. They, however, are completely left out of any housing schemes and face severe issues in regard to informal housing. The biggest issue in terms of strategy would be the lack of focus on climate resilience. There is no element of climate adaptation or disaster risk reduction in the housing scheme. Saudi Arabia faces numerous climate related risks including extreme temperatures, sudden flooding (specifically in Jeddah and Makkah) and water scarcity. Having no requirement for housing to be designed resiliently will leave them vulnerable in the long term. (Saudi Green Initiative 2021)

UN SUSTAINABLE DEVELOPMENT GOALS AND HOUSING

SDG 1: No Poverty

The UN 2030 Agenda for Sustainable Development provides the most comprehensive normative framework for housing within the context of integrated sustainable development. Five of the seventeen SDGs have direct relevance to housing and urban resilience. SDG 1 targets include ensuring that all men and women, particularly the poor and vulnerable, have equal rights to economic resources, access to basic services, and ownership of and control over land and other forms of property (UN 2015). Target 1.4 specifically addresses property rights and access to financial services, directly linking poverty eradication to housing tenure security and housing finance access. Inadequate housing is both a symptom and a cause of poverty: households insecure, substandard, or overcrowded housing face higher health costs, poorer educational outcomes for children, limited ability to accumulate assets, and greater vulnerability to economic shocks (Patel 2021).

SDG 8: Decent Work and Economic Growth

SDG 8 targets inclusive and sustainable economic growth and full productive employment. The housing construction sector is one of the most labour-intensive sectors of any economy, with significant forward and backward economic linkages. The SDG 8 framework thus supports housing

investment as an economic development mechanism, particularly when it generates local employment, promotes small and medium enterprise development in construction supply chains, and enables the productive use of slum-upgrading assets (ILO 2019).

SDG 9: Industry, Innovation, and Infrastructure

SDG 9 calls for building resilient infrastructure, promoting inclusive and sustainable industrialisation, and fostering innovation. In the housing context, this encompasses resilient building materials and construction practices, innovative housing finance mechanisms, digital infrastructure in residential developments, and the development of a sustainable housing construction industry. SDG 9.1 specifically calls for developing quality, reliable, sustainable, and resilient infrastructure to support economic development and human well-being. The key target is 9.1: quality, reliable, sustainable and resilient infrastructure that supports economic development and human well-being, with affordable and equitable access for all.

SDG 11: Sustainable Cities and Communities

SDG 11 is the most directly relevant goal for housing and urban development. Target 11.1 specifically commits to ensuring access for all to adequate, safe, and affordable housing and basic services, and upgrading slums by 2030. Target 11.3 addresses inclusive and sustainable urbanisation, 11.4 focuses on protecting cultural and natural heritage, 11.5 addresses disaster loss reduction, 11.6 targets urban environmental impact, and 11.7 ensures access to safe public spaces. New Urban Agenda (Quito 2016) operationalises SDG 11 with detailed implementation guidance.

SDG 13: Climate Action

SDG 13 calls for urgent action to combat climate change and its impacts. For the housing sector, this translates into the imperative for climate-resilient construction standards, risk-informed urban planning, integration of climate adaptation into housing programs, and mobilisation of climate finance for housing resilience investment. The IPCC's Sixth Assessment Report (2022) identifies housing as both a significant source of greenhouse gas emissions (through embodied carbon in construction and operational energy) and a critical adaptation frontier. Table 2 summarises the alignment of Saudi Vision 2030 and Pakistan's NHUP with the key SDG target.

PAKISTAN'S HOUSING AND URBAN DEVELOPMENT POLICIES

Housing crisis context

Pakistan is one of the fastest-urbanising countries in the

Table 1: Global housing challenge dimensions and selected indicators

Dimension	Global Estimate	Saudi Arabia	Pakistan	Relevant SDG
Housing Deficit	1.6 Billion persons	Estimated 200,000+ units/year demand	10–12 Million units	SDG 11.1
Informal Settlement Residents	1.1 Billion	≈5% urban population	≈45% urban population	SDG 11.1, SDG 1
Housing Finance Access	< 30% of adults in LMICs	Expanding; Sakani programme	< 10% of adults	SDG 8, SDG 1
Climate-Vulnerable Homes	1 Billion+	Heat & water stress	Flood/seismic risk acute	SDG 13, SDG 11
Housing Investment (% GDP)	5–8% typical	≈5% (growing)	≈3% (inadequate)	SDG 9



Fig. 1: Conceptual overview of the Saudi-Pakistan Affordable and Resilient Housing (SPARH) framework. The scene contrasts the housing contexts of the two countries: a rapidly urbanising Saudi Arabia guided by Saudi Vision 2030 (left), and a flood-exposed Pakistan guided by the National Housing and Urban Policy (NHUP; right). SPARH (centre) is shown as a single housing system aligned with the UN Sustainable Development Goals (SDGs 1, 8, 9, 11 and 13) and resting on a foundation of governance, data and accountability (underground layer). This foundation links delivery institutions (NHC, REDF, REGA), unified building codes and land records, a national housing data system, monitoring mechanisms and South-South cooperation. The framework is organised into four pillars (I–IV): affordability and financial inclusion, climate resilience and risk reduction, smart and inclusive infrastructure, and housing-economy linkages. Together they lead to four outcomes: affordable homes for all, climate-resilient communities, inclusive growth with decent jobs, and smart, sustainable cities.

Table 2: Alignment of Saudi Vision 2030 and Pakistan NHUP with key UN SDGs

SDG Target	Saudi Vision 2030 Alignment	Pakistan NHUP Alignment	Gap Assessment
SDG 1.4 (Property Rights and Finance)	Strong – REDF, Sakani mortgage support	Moderate – NPHP, housing finance expansion	Pakistan: credit access weak
SDG 8.3 (Inclusive Growth/Jobs)	Moderate – construction sector jobs	Strong – explicit employment focus in NPHP	Saudi: migrant workers excluded
SDG 9.1 (Resilient Infrastructure)	Moderate – building code reform	Weak – limited resilient infrastructure	Both: climate standards missing
SDG 11.1 (Adequate Housing)	Strong – Sakani, NHC programmes	Moderate – NPHP targets; delivery gaps	Pakistan: delivery gap; Saudi: equity gap
SDG 11.3 (Sustainable Urbanisation)	Strong – master-planned communities	Weak – rapid informal urbanisation	Pakistan: governance fragmented
SDG 11.5 (Disaster Loss Reduction)	Weak – no explicit DRR in housing	Weak – reactive post-disaster only	Both: DRR not mainstreamed
SDG 13.1 (Climate Resilience)	Absent – no climate adaptation in housing	Weak – post-2022 floods policy emerging	Critical gap in both frameworks

Table 3: Comparative policy matrix – Saudi vision 2030, UN SDGs, Pakistan NHUP

Policy Dimension	Saudi Vision 2030	UN SDGs (Relevant)	Pakistan NHUP	Synthesis Gap
Affordability Mechanisms	STRONG: Sakani, REDF subsidies, land tax	NORMATIVE: SDG 11.1 targets; no mechanism	MODERATE: NPHP, Mera Ghar; delivery gap	Finance depth & delivery capacity
Housing Finance Innovation	STRONG: REDF restructuring, mortgage market	NORMATIVE: SDG 8.3 inclusive finance	WEAK: <1% GDP mortgage depth	Inclusive finance for informal sector
Climate Resilience Standards	ABSENT: No explicit climate-housing linkage	STRONG: SDGs 9, 11.5, 13 norms	WEAK: Post-disaster only; no mainstreaming	Critical gap across all frameworks
Smart Urban Infrastructure	MODERATE: NHC smart communities pilot	NORMATIVE: SDG 9, 11.3 references	WEAK: Digital infrastructure limited	Technology-equity tension
Economic Development Linkage	MODERATE: GDP diversification rationale	STRONG: SDG 8 employment, SDG 9 industry	STRONG: NPHP employment emphasis	Monitoring & value chain integration
Governance and Institutional Capacity	STRONG: NHC, REDF, REGA institutional reform	NORMATIVE: SDG 17 partnerships	WEAK: Federal-provincial fragmentation	Data systems & accountability

world, with an urban population growing at approximately 3% per annum and projected to reach 50% of the total population by 2047 (Pakistan Bureau of Statistics 2022). Pakistan's urban areas are characterised by stark spatial inequality: Karachi, Lahore, and Islamabad host large formal residential sectors alongside vast katchi abadis (informal settlements) that house 45–60% of urban residents in many cities. The national housing shortfall—estimated at 10–12 million units, with an additional 700,000–900,000 units needed annually—reflects decades of underinvestment in housing policy and infrastructure. The housing finance market in Pakistan remains severely underdeveloped. Outstanding housing finance as a share of GDP stood at less than 1% in 2022, compared with a South Asian average of approximately 4% and a global average of approximately 40% (State Bank of Pakistan 2022). The formal banking sector predominantly serves upper-income households, while the bottom 60% of urban households—largely engaged in informal employment—are almost entirely excluded from formal mortgage products.

Naya Pakistan Housing Programme (NPHP)

The most significant recent housing policy initiative in Pakistan is the Naya Pakistan Housing Programme (NPHP),

launched under the Pakistan Tehreek-e-Insaf government in 2018–2019, with a target of delivering 5 million affordable housing units within five years. The NPHP introduced several innovative policy mechanisms: a government-backed mortgage scheme (Mera Pakistan Mera Ghar) offering subsidised loans at 3–5% interest rates; a construction technology park initiative to promote affordable building materials and techniques; and a partnership framework to engage private developers in affordable housing delivery on government-provided land.

The NPHP achieved some notable early results, including the issuance of approximately 400,000 mortgage approvals through the Mera Pakistan Mera Ghar scheme by 2022, and the initiation of several pilot housing colonies in Islamabad, Lahore, and KPK. However, the programme fell substantially short of its 5 million unit target, with fewer than 50,000 units in various stages of construction by 2022 (Pakistan Housing Authority Foundation 2022). Critics attributed these shortfalls to institutional fragmentation (housing is a devolved subject under the 18th Constitutional Amendment, creating coordination challenges between federal and provincial governments), land acquisition difficulties, lack of standardised building codes, and the absence of a functioning construction supply chain for affordable units.

Climate vulnerability and disaster risk

Pakistan's housing crisis intersects acutely with climate change and natural disaster risk. The country ranks among the world's ten most climate-vulnerable nations (Germanwatch 2021). The 2022 super-floods, described as a 'climate catastrophe,' submerged approximately one-third of Pakistan's total land area, displacing 33 million people, damaging or destroying 1.7 million homes, and causing estimated total economic damage of USD 30 billion (UNDP 2022). The floods exposed the catastrophic inadequacy of Pakistan's housing stock in climate-exposed areas: the vast majority of damaged homes were constructed from mudbrick or other kutcha materials without any flood-resistant features.

Pakistan's post-disaster housing reconstruction policies have historically focused on temporary shelter and ad hoc reconstruction without systematically integrating resilient building standards or risk-informed land use planning. The Resilient Recovery, Rehabilitation, and Reconstruction Framework (4RF), developed following the 2022 floods with international support, represents an important step toward integrating resilience into Pakistan's housing reconstruction agenda, but systematic integration into forward-looking housing policy has yet to be achieved.

Provincial policies and governance fragmentation

The 18th Constitutional Amendment (2010) devolved significant housing and urban development functions to Pakistan's four provinces (Punjab, Sindh, KPK, Balochistan) and federal territories. While devolution has enabled more context-specific policy, it has also created significant fragmentation in building codes, land administration systems, housing finance frameworks, and urban planning governance. The absence of a unified national housing data system makes accurate monitoring of housing need and programme delivery extremely difficult. The SPARH framework proposed in this paper explicitly addresses governance architecture as a critical enabling condition for effective affordable housing delivery.

COMPARATIVE POLICY ANALYSIS

Building on the documentary analysis and matrix developed in the Materials and Methods section, this section provides a systematic comparative analysis of the three policy frameworks on six dimensions (Table 3). The matrix shows three important discoveries. The first is that climate resilience is not represented in either national framework, although it is identified as a normative priority in the SDGs, and is the most important gap to address now. Second, the innovation and inclusion in housing finance is one of the critical weaknesses of Pakistan and one of the relative strengths of Saudi Arabia, thus making it possible to transfer knowledge from south to south. Third, the capacity of

governors and data systems are also basic enabling conditions, whose lack of strength in Pakistan has a basic and profound impact on programme delivery, regardless of the quality of the programme design. Perhaps the most striking thing that can be said about this is that across the frameworks, there is a strong focus on housing as an economic development engine. Saudi Vision 2030, like Pakistan's NPHP, sees housing investment as a way to create jobs, expand the private sector, and diversify the economy. This alignment with SDG 8 goals justifies the development of common frameworks based on the housing sector for wider economic development goals.

CASE STUDIES*Saudi Arabia: National Housing Company New Community Developments*

The National Housing Company (NHC) has been the primary vehicle for large-scale housing supply under Vision 2030. Its flagship projects include Al-Fursan City (Riyadh), a 10,000-unit mixed-income development integrating residential, commercial, and recreational uses; and Juman City (Eastern Province), a waterfront residential community targeting middle-income Saudi families. These developments exemplify the NHC's master-planned community model: land is acquired by the government, serviced with infrastructure, and then sold or developed in partnership with private sector developers.

Key lessons from the NHC model include: the effectiveness of integrated land preparation and infrastructure provision in reducing developer cost and risk; the challenge of ensuring affordability at the lower end of the income spectrum when market mechanisms are primary; the importance of location (several NHC projects have been criticised for peripheral locations disconnected from employment centres); and the pilot-stage adoption of green building features that have yet to be scaled systematically.

Pakistan: Naya Pakistan Housing Programme Pilot Projects

Pakistan's NPHP pilot projects in Islamabad's G-13 sector and KPK's Haripur district provide instructive evidence of the programme's strengths and limitations. The Islamabad pilot demonstrated the feasibility of government land preparation for affordable housing and the potential of subsidised mortgages to mobilise demand from middle-income households. However, the KPK pilot, intended to demonstrate delivery for lower-income rural-to-urban migrants, faced severe delays due to land acquisition disputes, contractor capacity limitations, and building material supply chain disruptions.

The 2022 floods provided an inadvertent case study in housing resilience failure. Post-flood assessments found that majority of the destroyed homes in Sindh and Balochistan

were constructed with non-engineered, non-resilient materials—a stark demonstration of the cost of neglecting resilient design standards in affordable housing. The government's post-flood reconstruction effort, supported by UNDP and the World Bank, has systematically incorporated resilient rebuilding standards for the first time, offering an important model for scaling.

International comparators

Singapore's Housing and Development Board (HDB) is widely regarded as one of the world's most successful public housing models, housing over 80% of Singapore's resident population in high-quality, well-located, and comprehensively serviced public housing estates. The HDB model's transferable lessons include long-term institutional continuity and political commitment; compulsory national savings (Central Provident Fund) mobilised for housing finance; systematic integration of social diversity, commercial services, and transit access in estate design; and ongoing asset upgrading programs that maintain housing quality over decades. While Singapore's city-state context limits direct transferability, the institutional architecture and finance mechanisms offer clear lessons for both Saudi Arabia and Pakistan.

South Africa's Breaking New Ground (BNG) programme, initiated in 2004 as a reform of the predecessor RDP housing programme, aimed to produce 'sustainable human settlements' rather than isolated housing units. BNG's emphasis on location efficiency, mixed-income community design, social services integration, and incremental upgrading of informal settlements offers relevant lessons for Pakistan's urban context. However, BNG has also been criticised for slow delivery and the persistence of spatial apartheid patterns, underscoring the importance of implementation capacity and political economy alongside good policy design.

RESULTS AND DISCUSSION

The conclusions that can be drawn from comparative analysis is important, not only in terms of theory, but also policy. One finding is that the affordability-resilience trade-off is a financing issue and not a technical one. Saudi Arabia and Pakistan have misleadingly marketed the construction of 'climate resilient' facilities as an 'extra expense' on the projects they seek to target. On the bright side, however, the evidence from international case studies and literature on disaster economics, is highly consistent in showing that the cost benefit ratio of resilience investment is positive over the building lifecycles (World Bank 2019). The lack of resilience investments is not an affordability issue, it's a financial market failure, short housing loan terms, low-risk premiums in the insurance market and the lack of foresight by the public sector in managing contingent disaster liabilities. Finding 2: The institutional

architecture is the salient constraint in Pakistan whereas the salient constraint is equity in Saudi Arabia. The comparative analysis reveals that the lack of institutional coherence, data systems and delivery capacity are the main issues in the housing programme in Pakistan which are universal and applicable to various policy designs and political leadership. However, the institutional reforms in Saudi Arabia (NHC, REDF, REGA) have established a functional housing delivery system, but there is a lack of development in the equity architecture, with lower-income Saudi households, women and migrant workers significantly under-served. The issue of housing inequality can be exacerbated by Smart Urbanism without Inclusive Design (Find 3). Although both countries have implemented smart urban infrastructure on housing, they have not paid attention to the costs for low-income citizens, and the community governance of smart systems. Research in other emerging-economy smart cities (India, Kenya, Indonesia) has been consistent that smart infrastructure can be exclusionary without an awareness of the need for equity. Challenging: SDG framework does not have an operational mechanism apart from the normative guidance. The UN SDG framework rightly targets the key drivers of the housing issue and establishes aspirational regulatory targets. The SDG monitoring framework is, however, not operationally detailed enough for policy design at country level: For example, SDG 11.1 does not specify the institutional design, the financing model or technical standards to achieve the SDG 11.1 at country level. The SPARH model is a chance to fill this gap with its operational framework, which it seeks to establish. Finding 5: There is much potential for knowledge transfer from South-South. The Saudi Pakistan economic, cultural and diplomatic ties are quite broad and extensive, including substantial remittance transfers by Pakistani migrant workers in Saudi Arabia and development finance. But little systematic knowledge sharing of housing policy has been observed. This is shown as a proposed model framework (SPARH) to operationalise this potential, in bilateral institutional mechanisms, development of joint research programs and technology transfer modalities.

THE SAUDI PAKISTAN AFFORDABLE AND RESILIENT HOUSING FRAMEWORK (SPARH)

Framework overview

The SPARH Framework is an original integrated policy model that synthesises the comparative analysis findings, international best practice lessons, and SDG normative standards into a four-pillar framework for affordable and resilient housing policy. The framework is designed to be applicable across both Saudi and Pakistani contexts while remaining adaptable to other emerging economy settings

confronting the combined challenges of housing affordability, climate resilience, and sustainable urban economic development. The four strategic pillars of SPARH are: (I) Housing Affordability and Financial Inclusion; (II) Climate Resilience and Disaster Risk Reduction; (III) Smart and Inclusive Urban Infrastructure; and (IV) Housing-Economic Development Linkages. These four pillars are supported by a cross-cutting enabling condition: Governance, Data, and Accountability Architecture. The pillars are conceptualised as mutually reinforcing progress in each pillar creates enabling conditions for the others, while weakness in any one pillar undermines the effectiveness of the overall framework. The framework is shown in Fig. 1.

Pillar I: Housing Affordability and Financial Inclusion

The first pillar addresses the supply-demand-finance triangle that determines whether housing is accessible to households across the income spectrum. Under SPARH, affordability policy is operationalised through three integrated sub-components.

The first sub-component is Inclusive Housing Finance, encompassing: (a) the development of mortgage products adapted to informal and variable income patterns, including 'step-up' mortgages where payments increase as household incomes grow; (b) community-based savings groups (following the Slum Dwellers International model) as complementary savings mechanisms; (c) risk guarantees to commercial lenders to crowd in private capital for low-income mortgage lending; and (d) Islamic finance instruments (murabaha, diminishing musharakah) adapted for low-income housing, highly relevant to both Saudi and Pakistani Muslim-majority contexts.

The second sub-component is Supply-Side Cost Reduction, encompassing: (a) public land banking and affordable lease mechanisms that separate land cost from housing development cost; (b) regulatory simplification (streamlined building permits, standardised planning requirements) to reduce time and cost of formal housing development; (c) industrialised construction technology promotion through government procurement preferences and construction technology centres; and (d) local materials development that reduces dependence on expensive imported construction materials.

The third sub-component is Demand-Side Targeting, encompassing: (a) income-graduated subsidies that target the deepest subsidies to the lowest-income quintiles while using market mechanisms for upper-income groups; (b) housing vouchers for rental support as an alternative to ownership subsidies for the most mobile or economically vulnerable households; and (c) cross-subsidy mechanisms within mixed-income developments that generate internal finance for below-market units.

Pillar II: Climate Resilience and Disaster Risk Reduction

The second pillar directly addresses the critical gap identified in both national frameworks. Under SPARH, climate resilience in housing is operationalised through mandatory standards, risk-informed planning, and innovative finance. Mandatory Resilient Building Standards would establish minimum resilience requirements calibrated to local hazard profiles (seismic zones, flood maps, heat extremes) for all formally permitted housing, phased over five years to allow supply chain and skills adaptation. These standards would cover structural resistance, flood-proofing passive cooling performance, and water efficiency, with technical specifications adapted from international standards and frameworks (ISO 13157 for flood resilience; the Sendai Framework for DRR).

Risk-Informed Urban Land Use Planning would integrate national hazard maps with formal land use planning systems to prohibit new formal housing development in high-risk zones and create incentive systems (density bonuses, infrastructure priority, expedited permits) for development in low-risk locations. This component requires significant investment in geospatial data infrastructure and planning capacity, particularly in Pakistan.

Resilience Finance Mechanisms would address the affordability-resilience financing gap through: (a) a Resilient Housing Fund that combines domestic budget allocation with climate finance from the Green Climate Fund, the Loss and Damage Mechanism, and bilateral climate finance to subsidize the resilience cost premium for low-income housing; (b) mandatory risk disclosure in housing markets that allows buyers to price resilience into property decisions; and (c) parametric disaster insurance products for low-income housing that provide rapid post-disaster reconstruction finance without the administrative burden of traditional insurance claims.

Pillar III: Smart and Inclusive Urban Infrastructure

The third pillar addresses the integration of digital and smart infrastructure into housing and neighbourhood design, with a central emphasis on inclusion and affordability of operational costs.

Inclusive Smart Infrastructure Standards would establish requirements for digital infrastructure in all new housing developments (fibre connectivity, smart metering, secure digital identity systems) while mandating community ownership of shared data and infrastructure rather than private vendor lock-in. Operational cost transparency requirements would ensure that smart infrastructure does not create unaffordable utility bills for low-income residents.

A digital housing management System would provide digital solutions to: Transparent allocation system for subsidized housing using digital waiting list systems property management systems to manage buildings

efficiently and effectively energy monitoring systems to reduce costs community information systems. Smart Urban Mobility ensures that housing locations are valued by ensuring that housing is located in sites that have good access to a transport network. This is achieved by requiring housing developments to be located within 800m of a transport network (Pillar III of SPARH). Cycles and pathways will also be included. Low-income residents will also have access to digital mobility systems.

Pillar IV: Housing Economic Development Linkages

The fourth pillar explicitly operationalises the relationship between housing investment and broader economic development goals, addressing a dimension that is recognised in both national frameworks but inadequately operationalised in either. Local Employment and Supply Chain Development standards within SPARH would require public housing developments above a threshold size to achieve minimum percentages of local labour (70%), local materials (50%), and local professional services (60%). Small and medium enterprise development programs would build construction sector capacity, particularly among women-owned enterprises and youth-owned businesses. Housing as Asset-Building for Households recognises that housing is the primary store of wealth for most low- and middle-income households. SPARH supports secure tenure for all housing (whether rental or ownership) as a precondition for households to use housing as an asset; improved property registration systems that reduce transaction costs and enable the use of housing as collateral for productive credit; and incremental building programs that allow households to invest in their own housing quality improvements over time.

Neighbourhood Economic Development Integration designs housing developments as nodes in broader urban economic systems rather than isolated residential enclaves. This includes mandatory provision of commercial and economic space within large housing developments; co-location of housing with employment zones, industrial parks, and economic development initiatives; and digital platforms connecting housing estate residents with local employment opportunities (Fig. 2).

Enabling condition: governance, data, and accountability

The SPARH framework recognises that high-quality policy design is insufficient without complementary governance architecture. The enabling condition layer specifies: a unified national housing data system that tracks housing need, supply, programme delivery, and outcome indicators against SDG and national targets; a multi-level governance architecture that coordinates national policy with provincial and local delivery, with clear role delineation and intergovernmental transfer mechanisms; independent programme monitoring and evaluation with public

reporting; meaningful community participation requirements in housing programme design and governance; and bilateral Saudi Pakistan institutional cooperation mechanisms (annual ministerial dialogue, joint research fund, technical exchange programme). Table 4 summarises the operational components, indicators, and SDG alignment of the framework

POLICY RECOMMENDATIONS

Based on the comparative analysis and the SPARH framework, this paper advances twelve specific policy recommendations for Saudi Arabia, Pakistan, and for bilateral and multilateral action.

Recommendations for Saudi Arabia

Recommendation 1: Extend the Sakani programme's reach to lower-income quintiles and to Saudi women entering the workforce for the first time through dedicated mortgage products with lower income thresholds and alternative credit assessment methodologies.

Recommendation 2: Introduce mandatory climate resilience standards in the National Building Code for all residential buildings, prioritising passive cooling performance, water efficiency, and flash flood resistance in coastal and valley locations. The Saudi Green Initiative (2021) already provides a normative anchor for this measure.

Recommendation 3: Develop a bilateral technical cooperation programme with Pakistan on housing finance innovation, specifically exploring the transfer of REDF financing models and Islamic finance housing products to the Pakistani context, including a joint Islamic Housing Finance Development Fund.

Recommendation 4: Expand the NHC's community development mandate to include economic development components—local enterprise development, job training centres, and digital economic infrastructure—within large-scale housing developments, thereby converting residential estates into mixed economic communities.

Recommendations for Pakistan

Recommendation 5: Establish a unified National Housing Data System under the Ministry of Housing, Works, and Urban Affairs, integrating data from all four provinces and federal territories, with annual public reporting against SDG 11.1 targets and national housing programme indicators.

Recommendation 6: Mainstream climate resilience into housing reconstruction and new housing programs by adopting a National Resilient Housing Code, calibrated by provincial hazard zones, as a precondition for public sector housing finance and subsidy eligibility.

Recommendation 7: Resolve the housing-sector governance fragmentation created by the 18th Amendment

Table 4: SPARH Framework – Operational Components, Indicators, and SDG Alignment

SPARH Pillar	Key Operational Component	Primary Indicator	SDG Alignment
I – Affordability & Finance	Inclusive mortgage products	% LI households with housing finance access	SDG 1.4, 8.3, 11.1
I – Affordability & Finance	Public land banking	Affordable units on public land (annual)	SDG 11.1, 10.2
II – Resilience & DRR	Mandatory resilient building standards	% new units meeting resilience code	SDG 11.5, 13.1, 9.1
II – Resilience & DRR	Risk-informed land use planning	% housing in low-risk zones	SDG 11.3, 13.1
II – Resilience & DRR	Resilience Finance Fund	Annual climate finance for housing (USD M)	SDG 13.a, 17.3
III – Smart Urban	Digital infrastructure in housing	% units with broadband connectivity	SDG 9.c, 11.3
III – Smart Urban	Transit-accessible site selection	% units within 800m of public transport	SDG 11.2, 11.3
IV – Economic Linkage	Local employment standards	% local labor in public housing projects	SDG 8.3, 8.5
IV – Economic Linkage	Secure tenure for all	% households with documented tenure	SDG 1.4, 11.1
Enabling: Governance	National housing data system	Data completeness & timeliness score	SDG 17.18

through a National Housing Coordination Council that brings together federal and provincial housing authorities, with a statutory mandate for intergovernmental coordination and minimum national standards.

Recommendation 8: Scale the Mera Pakistan Mera Ghar programme with specific targeting of informal sector workers through salary or income verification via digital payment records, mobile money transaction history, or employer cooperatives, thereby reducing the exclusion of the informal sector from formal housing finance.

Bilateral and multilateral recommendations

Recommendation 9: Establish a Saudi Pakistan Housing Cooperation Initiative under the ambit of the Saudi Fund for Development, with dedicated funding for Pakistani affordable and resilient housing projects that pilot SPARH framework components in Pakistan’s peripheral cities.

Recommendation 10: Both countries should develop and submit to UNFCCC their National Adaptation Plans (NAPs) with specific chapters on housing sector climate adaptation, enabling access to the Green Climate Fund’s adaptation financing window for housing resilience programs.

Recommendation 11: Engage UN-Habitat as a technical partner for the development and operationalisation of the SPARH framework, leveraging UN-Habitat’s global programme expertise, knowledge platform, and advocacy access to position SPARH as a model for bilateral housing cooperation among other emerging economies.

Recommendation 12: Both governments should invest in joint research and professional exchange programs in affordable and resilient housing design, construction technology, and urban planning, building the professional human capital pipeline needed for long-term housing programme delivery.

CONCLUSION

The present paper has thus conducted a comprehensive comparative policy analysis of the housing agenda in Saudi Vision 2030, the UN Sustainable Development Goals pertaining the housing and urban development and the

National Housing and Urbanisation Policy of Pakistan. The paper, through structured documentary analysis, the multi criteria comparative matrix and case study review, has identified critical gaps, convergences and opportunities for policy learning across these three frameworks. The main conclusion is that both Saudi Arabia and Pakistan have progressed substantially towards establishing a more ambitious housing policy and improving institutional development in the last few years, but both housing policy frameworks have a critical and common strategic gap: the lack of systematic incorporation of climate resilience and disaster risk reduction into affordable housing programs. This is not only a policy oversight but is fundamentally threatening the housing investment programs in both countries, as there is growing evidence of climate related extremes happening at a greater frequency as seen in the floods of 2022 in Pakistan as reported by the IPCC. The SDG framework, with its targets and goals, is the normative mandate to address this gap, and an operational translation is needed now. The paper is an original contribution to the literature and to the practice of policymaking, presented here under the name of Saudi Pakistan Affordable and Resilient Housing Framework (SPARH). SPARH offers an enabling framework that brings the four strategic pillars (housing affordability and financial inclusion, climate resilience and disaster risk reduction, smart and inclusive urban infrastructure, and housing economic development linkages) together in an operationally grounded approach to housing policy development that goes beyond the existing approach in both countries. The SPARH framework is provided as a guide to policy dialogue, adaptation and contextualisation, not as a blueprint to be implemented. Political economy, culture, institutional history and fiscal capacity are all part of housing policy and need to be understood locally and involve communities. The real strength of the framework is the common language, the analytical dimensions, and the operational components which open the framework to the Saudi and Pakistani policy makers, practitioners, civil society and international partners for structured policy dialogue. The context of the Saudi Pakistan bilateral is just one of the many factors. The urbanisation, housing shortages, increased climate

vulnerability and budget constraints that affect both countries are common to dozens of emerging and developing economies. The contribution of the SPARH framework to the long-term future is, perhaps, its potential as a transferable model which can be adapted for different country pairs and/or regional groupings to fit their local context. In an era of increased global housing pressure and of the fast-approaching opportunity to fulfil SDG 11 targets, innovative bilateral approaches, which build on complementary national strengths and capacities towards a shared housing agenda, are a much-needed element in the international development architecture. Further studies are needed to empirically test the SPARH framework components in pilot programs in both countries, to rigorously evaluate the affordability-resilience trade-off under various financial scenarios, and to create a digital decision-support tool to operationalise the SPARH planning model for local housing development authorities.

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Effects of Iron Nanoparticles and Salinity on Growth and Physiology of Onion (*Allium cepa*)

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ABSTRACT

Background: Salinity is one of the most significant abiotic stresses affecting crop production, which affects plant growth, photosynthesis, oxidative balance and nutrient uptake. The application of nanotechnology, especially the iron nanoparticles (Fe-NPs) is a promising strategy for enhancing plant tolerance to saline environments.

Objective: The objective of this study was to investigate the role of spinach-mediated iron nanoparticles in alleviating salinity-induced damage in onion (*Allium cepa* L.) in terms of growth, physiological, biochemical and mineral responses.

Methodology: The pot experiment was carried out in 3 × 4 factorial completely randomized design (3 replicates) with salinity: 0, 150 and 200 mM NaCl and Fe-NP foliar application: 0, 250, 350 and 450 ppm. The growth parameters, photosynthetic pigments, oxidative stress parameters, antioxidant metabolites and mineral nutrients were measured by standard procedures.

Results: The salinity reduced growth, photosynthetic contents, and nutrient accumulation, and increased the malondialdehyde (MDA) accumulation that suggests increased oxidative damage. Foliar Fe-NPs improved growth parameters, increased chlorophyll (a & b) and carotenoids, and decreased lipid peroxidation, while increasing antioxidant compounds such as flavonoids, ascorbic acid, and phenolics. Fe-NPs also positively affected mineral nutrient balance by enhancing the Fe accumulation and minimizing ionic disturbances due to salinity. The greatest ameliorative action was observed at 450 ppm.

Conclusion: The spinach mediated iron nanoparticles significantly reduced the physiological and biochemical constraints of onion under salinity stress by enhancing photosynthetic pigments, antioxidant defense and nutrient homeostasis. Iron nanoparticles are a promising approach to enhance onion performance under salinity stress.

INTRODUCTION

Salinity is one of the major abiotic stresses affecting agricultural productivity in areas where irrigation and soil conditions lead to the buildup of soluble salts. Exposure to higher concentrations of salt for longer periods leads to reduced plant growth, photosynthesis, metabolic activity,

water uptake and ionic balance (Attiq *et al.* 2021), eventually causing a reduction in yield of crops (Raphael and Parthasarathi 2026). Salinity effects are especially evident in the disruption of the photosynthetic processes. Salt-induced water limitation and ionic imbalance may cause decreased pigment accumulation and impairment of photosynthetic machinery (Liu *et al.* 2019). Thus,

chlorophyll (a, b and total chlorophyll) and carotenoids are good markers to assess plant physiological response to salinity (Bistgani *et al.* 2019). Another consequence of salt exposure is the increased formation of reactive oxygen species (ROS). When ROS production becomes excessive, cellular membranes and other macromolecules may be damaged. One outcome is lipid peroxidation and the associated accumulation of malondialdehyde (MDA), which is widely used to assess membrane injury. Plants also rely on non-enzymatic antioxidants, including phenolics, flavonoids, and ascorbic acid, to strengthen their antioxidant protection (Kanwal *et al.* 2024). Mineral nutrition is also affected by salinity because the accumulation of Na^+ can interfere with the uptake and distribution of other essential ions, particularly K^+ . The ability to maintain ionic balance is therefore important for several processes, including enzyme activity, osmotic adjustment, stomatal functioning, and photosynthetic metabolism (Zamir *et al.* 2026). Consequently, implementation of efficient strategies to improve nutrient status while limiting salt-induced ionic disturbances may contribute to greater plant tolerance.

Onion is an economically important vegetable crop cultivated extensively in many agricultural systems (Sekara *et al.* 2017). Its productivity depends on adequate vegetative development, efficient nutrient acquisition, and efficient photosynthetic machinery. However, salinity stress can substantially impair onion growth by reducing morphological attributes, including shoot and root development, leaf number, leaf area, and fresh and dry biomass accumulation (Patil *et al.* 2026). Nanotechnology provides a potential approach for improving plant resilience to combat various stresses like salinity (Al-Khayri *et al.* 2023). Iron is an essential micronutrient involved in important metabolic and photosynthetic processes, and nanoparticle-based Fe delivery may provide an alternative means of supplying Fe to stressed plants (Sen *et al.* 2025). Plant extracts particularly attractive approach to obtain green-synthesized nanoparticles such as iron, because plant-derived compounds can participate in nanoparticle formation and may provide an alternative to conventional synthesis routes (Shahzadi *et al.* 2025). Although the beneficial effects of nanoparticles in improving salt tolerance have been reported in several crops, very limited information is available relevant to the integrated response of green-synthesized iron nanoparticles under salinity stress in onion plants, particularly considering growth performance, photosynthetic pigments, oxidative stress responses, and mineral nutrient balance. We hypothesized that foliar application of spinach-mediated iron oxide nanoparticles would partially alleviate salinity-induced damage in onion by improving growth and photosynthetic pigment accumulation, strengthening antioxidant-related responses, and improving mineral nutrient balance. Therefore, this study is directed to investigate the influence of various concentrations of spinach-mediated iron oxide nanoparticles on growth and physiological characteristics of

onion plants under saline conditions. For this purpose, influence of nanoparticles under high salt contents on photosynthetic pigments, oxidative-stress-related attributes, and changes in mineral nutrient accumulation, particularly K^+ , Na^+ , and Fe, is determined.

MATERIALS AND METHODS

Experimental site and soil preparation

The experiment was conducted during 2023–2024 in the Department of Botany, Ghazi University, Dera Ghazi Khan, Pakistan. Soil samples were collected from the upper 0–30 cm layer of an experimental site located in the Department of Botany, Dera Ghazi Khan. The soil was air-dried for approximately three days, crushed, cleared of stones and other coarse materials, then passed through a 2 mm sieve for further cleaning. After that, physicochemical properties were analysed by standard analysis protocols (Table 1).

Plant material and experimental design

The experiment was designed to estimate the influence of salinity stress and foliar-applied spinach-mediated iron nanoparticles (Fe-NPs) on onion (*Allium cepa* L.) plants. The design was completely randomized (CRD) with a factorial arrangement of treatments. In a controlled environment, plant seedlings were grown in pots. After thirty days of seedling establishment, saline stress was applied. Three concentrations of NaCl (0, 150, and 200 mM) were applied in combination with foliar application of Fe-NP (0, 250, 350, and 450 ppm) as a mitigant.

Table 1: Physicochemical properties of soil

Soil characters	Value
Texture of soil	Sandy loam
pH	7.8
EC_e	4.90 dS m^{-1}
Saturation (%)	42
Organic matter (%)	0.56
Available phosphorus (mg kg^{-1})	8.47
Available potassium (mg kg^{-1})	151

Synthesis of nanoparticles

By using Abert *et al.* (2022) method synthesis of iron-based nanoparticles was done in the laboratory of the Botany Department at Ghazi University, Dera Ghazi Khan. The iron oxide nanoparticles were extracted from spinach (*Spinacia oleracea*). For this purpose, ferric chloride hexahydrate was mixed with ferrous chloride tetrahydrate (1:2 molar ratio), then dissolved in 100 mL of water. The mixture was heated at 80 °C with constant stirring. After 10 min, spinach extract (20 mL) was added. The solution changed color from pale yellow to dark brown, indicating the formation of nanoparticles. For controlled precipitation of Fe-nanoparticles, 20 mL of sodium hydroxide was added

gradually (3 mL per min). The mixture was left to cool at ambient temperature. Then decantation was done to get the nanoparticles. To remove the impurities, thorough rinsing was done using distilled water. Then dried at room temperature for experimental use.

Data collection and analysis

Plants were uprooted approximately 15 days after Fe-NP treatment for morphological, physiological, and elemental analysis measurements. For fresh and dried analysis, harvested plants were stored carefully. For fresh analysis, plants were labeled, placed in zipper bags, and frozen at -40°C . For dry analysis, half of harvested plants were put in brown bags, then oven-dried for 1 week at 65°C .

Growth parameters

For fresh biomass determination, plants were uprooted, shoots and roots were separated and weighed immediately on a top-load weight balance. The plant shoots and roots were put in brown bags, then, for complete drying, placed in an oven at 65°C and then weighed on a top-load weight balance.

Photosynthetic pigments

Arnon (1949) and Davies (1977) methods were used to determine photosynthetic contents of onion plants by using fresh leaves. 0.1 g of sample was ground with 5 mL of acetone (80%). The solution was filtered to take readings at various wavelengths (480, 663, and 645 nm) using a spectrophotometer. For final calculations, the following formulas were used:

$$\begin{aligned}\text{Chl. } a \text{ (mg/g f. wt.)} &= [12.7(A_{663}) - 2.69(A_{645})] \times 5/1000 \times 0.1 \\ \text{Chl. } b \text{ (mg/g f. wt.)} &= [22.9(A_{645}) - 4.68(A_{663})] \times 5/1000 \times 0.1 \\ \text{Carotenoids (mg/mL)} &= [(A_{480}) + 114(A_{663}) - 0.638(A_{645})] \times V/2500 \times W\end{aligned}$$

Oxidative stress and antioxidants

Heath and Packer (1968) method was used to determine malondialdehyde in plants to measure lipid peroxidation. Fresh samples of roots and shoots (0.5 g) were ground with 5 mL trichloroacetic acid (TCA; 5%), centrifuged (15 min), and the supernatant collected. Mixed with TBA (thiobarbituric acid) and incubated for 25 min (100°C). Measurements were taken at 533 and 600 nm.

Flavonoid concentration was determined separately in leaf and root tissues using the Zhishen *et al.* (1999) method with fresh plant extract. For extraction, methanol (80%) was used. Sodium nitrate and hydroxide were added to the plant extract with aluminum chloride. The readings were noted at 510 nm using a spectrophotometer. Final readings were calculated using a standard curve. To measure the total phenolic content in roots and shoots Julkunen-Tiitto (1985) Folin-Ciocalteu colorimetric assay was used. Fresh root and

shoot samples were ground with acetone (80%). Extracted and mixed with reagent (Folin-Ciocalteu) and sodium carbonate solution. At 730 nm readings were noted using a spectrophotometer.

Fresh roots and leaves were used to determine ascorbic acid content by following the Gillespie and Ainsworth (2007) method. Samples were ground with metaphosphoric acid (5%) and centrifuged. Supernatant collected and mixed with 2,6-dichlorophenol indophenol. Using a spectrophotometer, readings were noted at 520 nm.

Elemental analysis

0.5 g of dried plants were digested with concentrated acid (HNO_3). Added distilled water for final volume of 50 mL. To estimate phosphate-P contents Yoshida *et al.* (1971) procedure was used. The digested sample was mixed with HNO_3 (2N) and reagent (molybdate-vanadate). Incubated (20 min), and values were taken at 420 nm. Kowalenko and Lowe (1973) procedure was followed to calculate nitrate-N. The digested sample was mixed with CTA (chromotropic acid). Values were taken at 430 nm. Atomic absorption was used to estimate potassium, iron, and sodium using digested samples.

Statistical analysis

The experimental factorial design was completely randomized. Salinity and nanoparticle concentrations were recorded as two factors. For analysis of data, two-way analysis of variance (ANOVA) was used to evaluate the influence of salinity concentrations on Fe nanoparticle levels in Statistix 8.1 software. Then Tukey's test was used for further analysis, where significance was at $P \leq 0.05$. Origin software was used to represent graphical pictures of results, where values were shown as mean $\pm$ standard error (SE).

RESULTS

Growth attributes

ANOVA showed that salinity and foliar-applied Fe-NP significantly affected onion growth attributes. The interaction between salinity levels and Fe-NP treatments was significant ($P < 0.05$) for shoot and root biomass parameters (Fig. 1). Salinity stress significantly reduced shoot (fresh and dry) and root (fresh and dry) weights as compared to control plants. Increasing levels of NaCl (0, 150, and 200 mM) progressively decreased biomass accumulation, and the lowest values were recorded under 200 mM NaCl without Fe-NP application. It was observed at 200 mM NaCl there was more decline in growth compared to 150 mM salinity. However, exogenous application of Fe-NP significantly enhanced

growth traits in normal and saline conditions. Compared with untreated plants, Fe-NP-treated plants showed increased shoot and root biomass, with a progressive improvement as Fe-NP concentration increased. Shoot and root (fresh and dry) weights were enhanced at 450 ppm Fe-NPs, followed by 350 and 250 ppm Fe-NPs treatment.

Photosynthetic pigments

Statistical analysis revealed that salinity stress and foliar Fe-NP application significantly affected photosynthetic pigment contents of onion plants. Salinity significantly diminished chlorophyll (a, b & total) and carotenoid contents, whereas Fe-NP application significantly improved pigment accumulation in non-stress and stress conditions (Fig. 2). The interaction between salinity and Fe-NP treatments showed significant variation among treatment combinations ($P < 0.05$). Results showed that increasing NaCl concentration from 0 to 150 and 200 mM significantly decreased chlorophyll *a* and *b* content. The maximum reduction was observed under 200 mM NaCl without Fe-NP application, whereas control plants maintained the highest chlorophyll *a* concentration. Foliar-applied Fe-NPs significantly improved chlorophyll (*a* & *b*) contents, and maximum enhancement was recorded in 450 ppm Fe-NPs followed by 350 ppm and 250 ppm treatments under normal and stress conditions.

High salt contents significantly reduced the total chlorophyll contents, whereas Fe-NP application progressively increased chlorophyll accumulation. The highest value of total chlorophyll was observed under 450 ppm Fe-NPs, followed by 350 ppm and 250 ppm treatments, demonstrating the protective effect of Fe-NPs on the photosynthetic apparatus under salt stress. Carotenoid contents also showed significant variation among salinity $\times$ Fe-NP combinations. Increasing NaCl concentration reduced carotenoid accumulation, while Fe-NP application significantly improved carotenoid content under stress conditions.

Oxidative stress and antioxidant responses

Salinity and foliar Fe-NP application significantly influenced oxidative stress and antioxidant metabolites in onion (Fig. 3a, 3b). Their interaction was also significant ($P < 0.05$), as reflected by the different Tukey grouping letters among treatment combinations.

MDA accumulation increased significantly in both leaf and root tissues under salinity and reached its highest level at 200 mM NaCl, indicating greater lipid peroxidation. Foliar Fe-NP application lowered MDA relative to untreated salt-stressed plants. In contrast, flavonoids, ascorbic acid, and total phenolics generally increased following Fe-NP application. The highest antioxidant accumulation occurred

at 450 ppm Fe-NPs, followed by 350 and 250 ppm. Thus, Fe-NP treatment was associated with lower oxidative damage and stronger antioxidant responses under saline conditions (Fig. 3a, 3b).

Elemental composition

Statistics revealed that salinity and foliar-applied Fe-NP significantly affected mineral nutrient accumulation in onion plants (Fig. 4a, 4b, 4c). The salinity $\times$ Fe-NP interaction was significant ($P < 0.05$) for all analysed elements except leaf potassium, which showed a non-significant interaction ($P > 0.05$). Increasing NaCl concentration disturbed mineral balance by decreasing essential nutrient accumulation and increasing sodium levels, particularly under 200 mM NaCl stress. Foliar Fe-NP application significantly improved nutrient status under saline conditions by enhancing iron accumulation, improving potassium retention, and reducing excessive sodium accumulation. Iron concentration in leaf and root tissues increased progressively with increasing Fe-NP levels, with the maximum accumulation recorded under 450 ppm Fe-NPs, followed by 350 and 250 ppm treatments. Similarly, Fe-NP application improved nitrate and phosphate accumulation under salt stress. Overall, Fe-NPs enhanced nutrient acquisition and helped to maintain ionic homeostasis under saline conditions.

Correlation matrix

Pearson correlation of treatment means showed tight coupling among most traits (Fig. 8). Growth traits (shoot and root fresh and dry weight) were strongly positively correlated with chlorophyll *a*, chlorophyll *b*, total chlorophyll, carotenoids, nitrate, phosphate, potassium, iron and phenolics ($r = 0.84$ to 0.99 , $P < 0.001$). The same growth traits were strongly negatively correlated with leaf and root MDA ($r \approx -0.95$ to -0.98 , $P < 0.001$) and with leaf and root sodium ($r \approx -0.95$ to -0.96 , $P < 0.001$). Sodium itself was strongly positively correlated with MDA ($r \approx 0.96$ to 0.97 , $P < 0.001$). Nitrate, phosphate and potassium were strongly positively correlated with one another ($r \geq 0.99$) and negatively correlated with sodium ($r \approx -0.83$ to -0.89 , $P < 0.001$). Flavonoids and ascorbic acid were only weakly or moderately correlated with the other traits ($|r| \leq 0.57$), so they did not track the growth and nutrient response (Fig. 5).

DISCUSSION

Salinity affects crop productivity by causing osmotic imbalance, ionic toxicity, oxidative damage and disrupting normal physiological processes. The onion growth such as shoot and root biomass decreased with the increase of NaCl concentration in this study. Salinity-induced growth

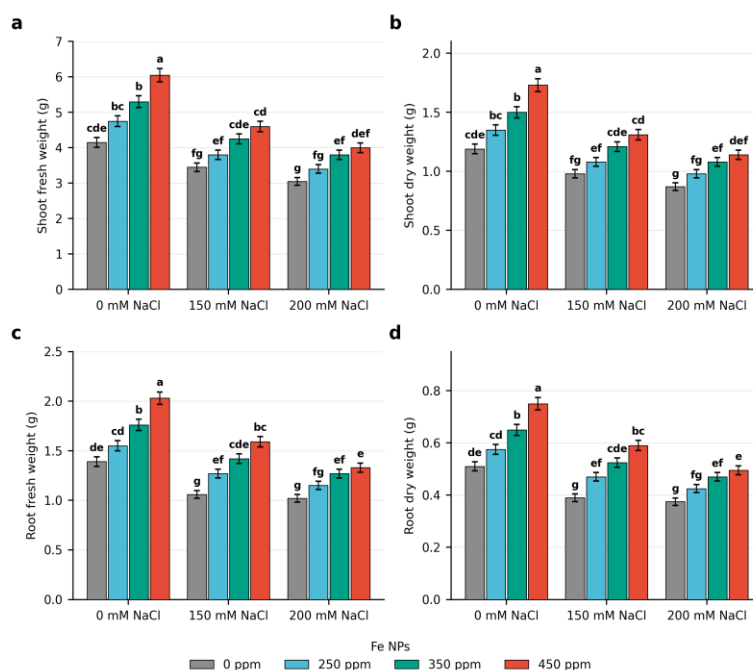


Fig. 1: Foliar application of spinach-mediated iron nanoparticles (Fe NPs) improves growth of onion plants under salinity stress. a, Shoot fresh weight. b, Shoot dry weight. c, Root fresh weight. d, Root dry weight. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Data are mean $\pm$ SE. Different letters indicate significant differences among treatments ($P \leq 0.05$).

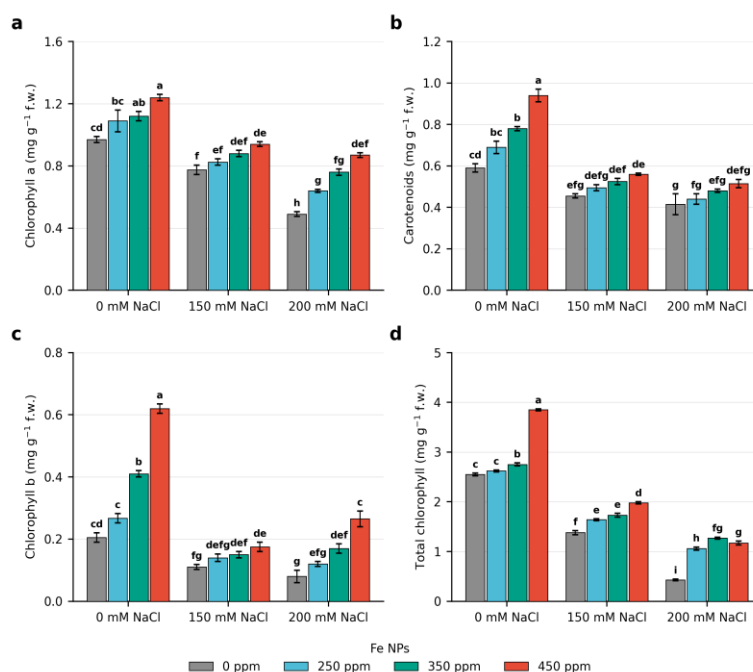


Fig. 2: Spinach-mediated iron nanoparticles (Fe NPs) restore photosynthetic pigments in onion plants under salinity stress. a, Chlorophyll a. b, Carotenoids. c, Chlorophyll b. d, Total chlorophyll content. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Pigment contents are expressed as mg g⁻¹ fresh weight (FW). Data are mean $\pm$ SE. Different letters indicate significant differences among treatments ($P \leq 0.05$).

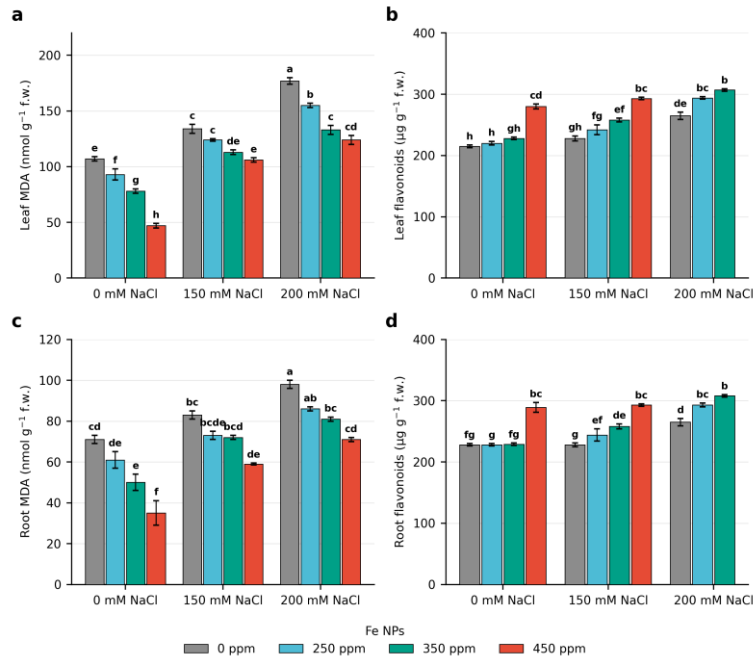


Fig. 3a: Foliar application of spinach-mediated iron nanoparticles (Fe NPs) improves growth of onion plants under salinity stress. a, Shoot fresh weight. b, Shoot dry weight. c, Root fresh weight. d, Root dry weight. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Data are mean ± SE. Different letters indicate significant differences among treatments ($P \leq 0.05$).

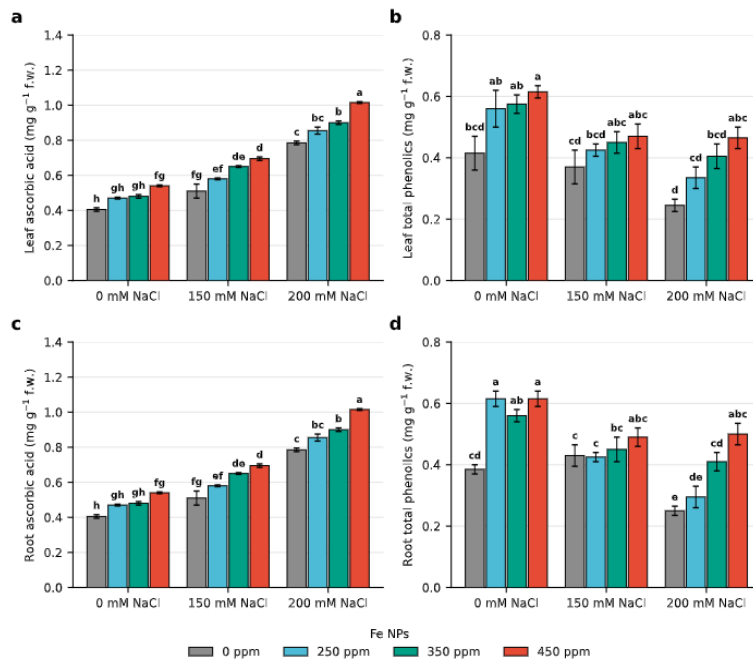


Fig. 3b: Spinach-mediated iron nanoparticles (Fe NPs) enhance non-enzymatic antioxidants in onion plants under salinity stress. a, Leaf ascorbic acid. b, Leaf total phenolics. c, Root ascorbic acid. d, Root total phenolics. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Contents are expressed as mg g⁻¹ fresh weight (f.w.). Data are mean ± SE. Different letters indicate significant differences among treatments ($P \leq 0.05$).

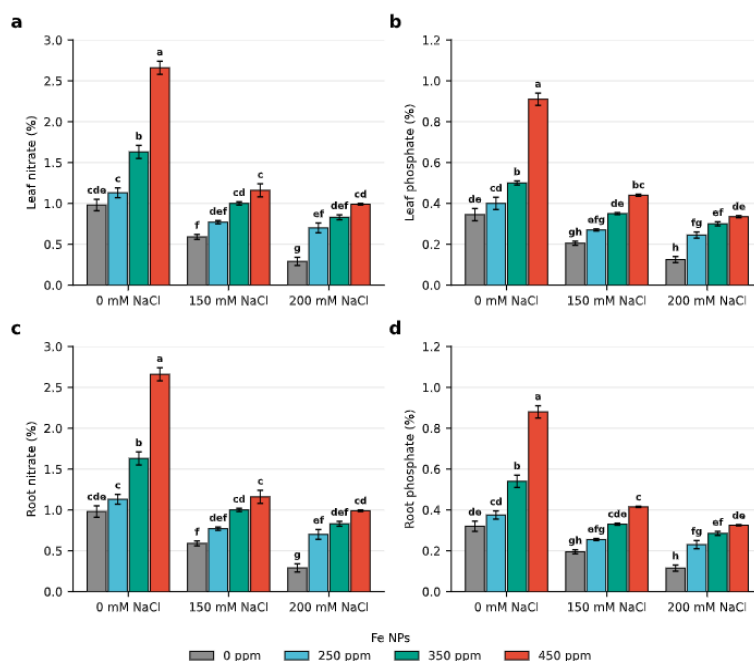


Fig. 4a: Spinach-mediated iron nanoparticles (Fe NPs) improve nitrate and phosphate accumulation in onion plants under salinity stress. a, Leaf nitrate. b, Leaf phosphate. c, Root nitrate. d, Root phosphate. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Contents are expressed as a percentage (%). Data are mean $\pm$ SE. Different letters indicate significant differences among treatments ($P \leq 0.05$).

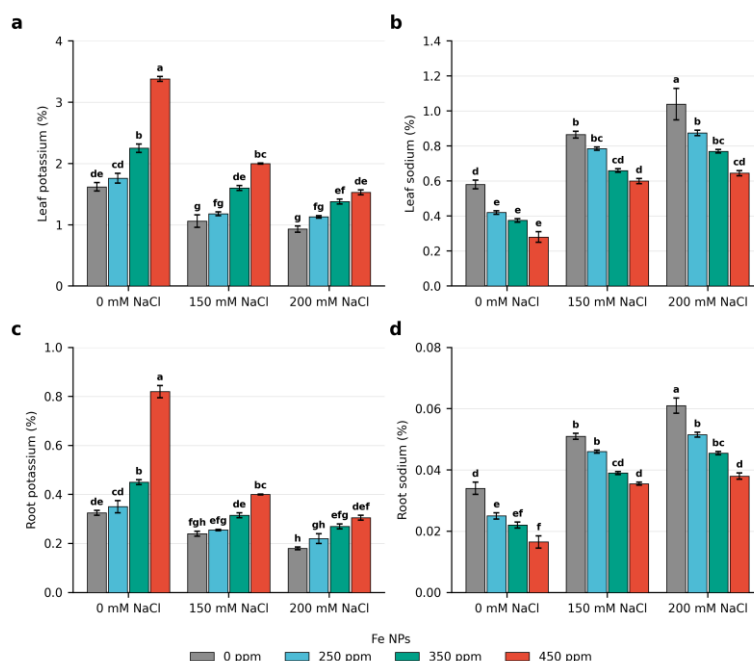


Fig. 4b: Spinach-mediated iron nanoparticles (Fe NPs) increase potassium and reduce sodium accumulation in onion plants under salinity stress. a, Leaf potassium. b, Leaf sodium. c, Root potassium. d, Root sodium. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Contents are expressed as a percentage (%). Data are mean $\pm$ SE. Different letters indicate significant differences among treatments according to Tukey's test ($P \leq 0.05$).

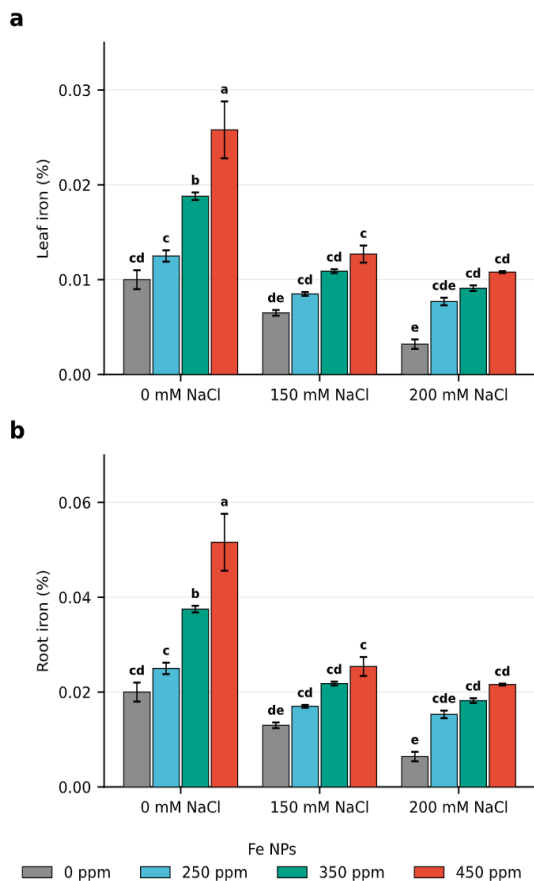


Fig. 4c: Spinach-mediated iron nanoparticles (Fe NPs) increase iron accumulation in onion plants under salinity stress. a, Leaf iron. b, Root iron. Plants were grown under 0, 150 or 200 mM NaCl and sprayed with Fe NPs at 0, 250, 350 or 450 ppm. Iron content is expressed as a percentage (%). Data are mean $\pm$ SE. Different letters indicate significant differences among treatments according to Tukey's test ($P \leq 0.05$).

inhibition can be due to cell growth limitation, reduction in water availability, decreased uptake of nutrients, and the build-up of Na^+ ions (Balasubramaniam *et al.* 2023). Ion balance of cells is also affected by high salt concentrations, and this disturbs metabolic activity leading to a decreased biomass production (Gul *et al.* 2022). Results indicated that the activity of growth inhibition increased with NaCl concentration, being more pronounced at 200 mM than at 150 mM. Foliar-applied spinach-mediated Fe-NPs significantly improved root and shoot biomass under high salt contents, demonstrating their protective role against salt-induced growth inhibition. Iron is considered an essential nutrient because of its involvement in chlorophyll biosynthesis, respiratory machinery, electron transport, and various other enzymatic activities (Rai *et al.* 2021). Improved Fe availability through nanoparticle application can enhance metabolic activity and nutrient utilization, which has been shown to enhance plant growth under stress

(Zia-ur-Rehman *et al.* 2023). The increase in surface area and bioavailability of Fe-NPs facilitates efficient nutrient delivery compared with conventional iron sources. A meta-analysis of Fe-based nanomaterials reported that Fe-NPs significantly improve plant biomass, antioxidant activity, and stress tolerance by enhancing nutrient availability and reducing oxidative damage (Tan *et al.* 2026). The application of iron-based nanoparticles improved growth and physiological characteristics of wheat plants by enhancing biomass productivity and reducing salt-induced damage (Singh *et al.* 2025).

The reductions in chlorophyll *a*, chlorophyll *b*, and carotenoids under high salinity indicate disturbance of the photosynthetic system. Under salt stress, chlorophyll level can be reduced due to limitation in its biosynthesis, increased degradation and oxidative damage to chloroplast membranes (Li *et al.* 2015). Carotenoids also play a role in photoprotection, through their ability to dissipate excess excitation energy and to scavenge ROS. They could then be expected to display less photoprotection under conditions of high salinity (Ramachandran *et al.* 2023).

Fe-NP application resulted in an increase in photosynthetic pigments, indicating the alleviating effect of Fe supply on the protection of pigment-related processes under salt stress. Iron is associated with chlorophyll biosynthesis and electron transfer via iron-containing proteins such as ferredoxin and cytochromes. Similarly, Fe-NPs were seen to enhance PSII activity and photosynthetic performance and pigment stability under saline conditions. The carotenoids increased following the treatment with Fe-NP, which is also consistent with enhanced protection from photo-oxidative damage and oxidative injury. Kreslavski *et al.* (2023) similarly reported that Fe_3O_4 nanoparticles improved photosynthesis, PSII activity, and pigment stability under saline conditions. The increase in carotenoids observed after Fe-NP treatment is also consistent with improved photoprotection and lower oxidative injury.

The rise in malondialdehyde (MDA) in onion leaves and roots showed that salinity increased oxidative stress in the present study. Higher MDA is associated with lipid peroxidation and membrane injury resulting from excessive ROS production (Nawaz *et al.* 2025). Under saline conditions, disruption of electron transport and other metabolic processes can increase ROS formation, thereby affecting membrane stability and cellular function (Hameed *et al.* 2021).

The decline in MDA after Fe-NP application indicates that oxidative injury was reduced. Iron participates in antioxidant metabolism, including as a cofactor in several antioxidant enzymes, and Fe-NPs may influence ROS-scavenging and cellular redox regulation (Kejik *et al.* 2021). In the present study, Fe-NP application also increased flavonoids, ascorbic acid, and phenolic compounds, showing a stronger non-enzymatic antioxidant response. Phenolics and flavonoids can directly scavenge ROS, while ascorbic acid contributes to regulation of the cellular redox

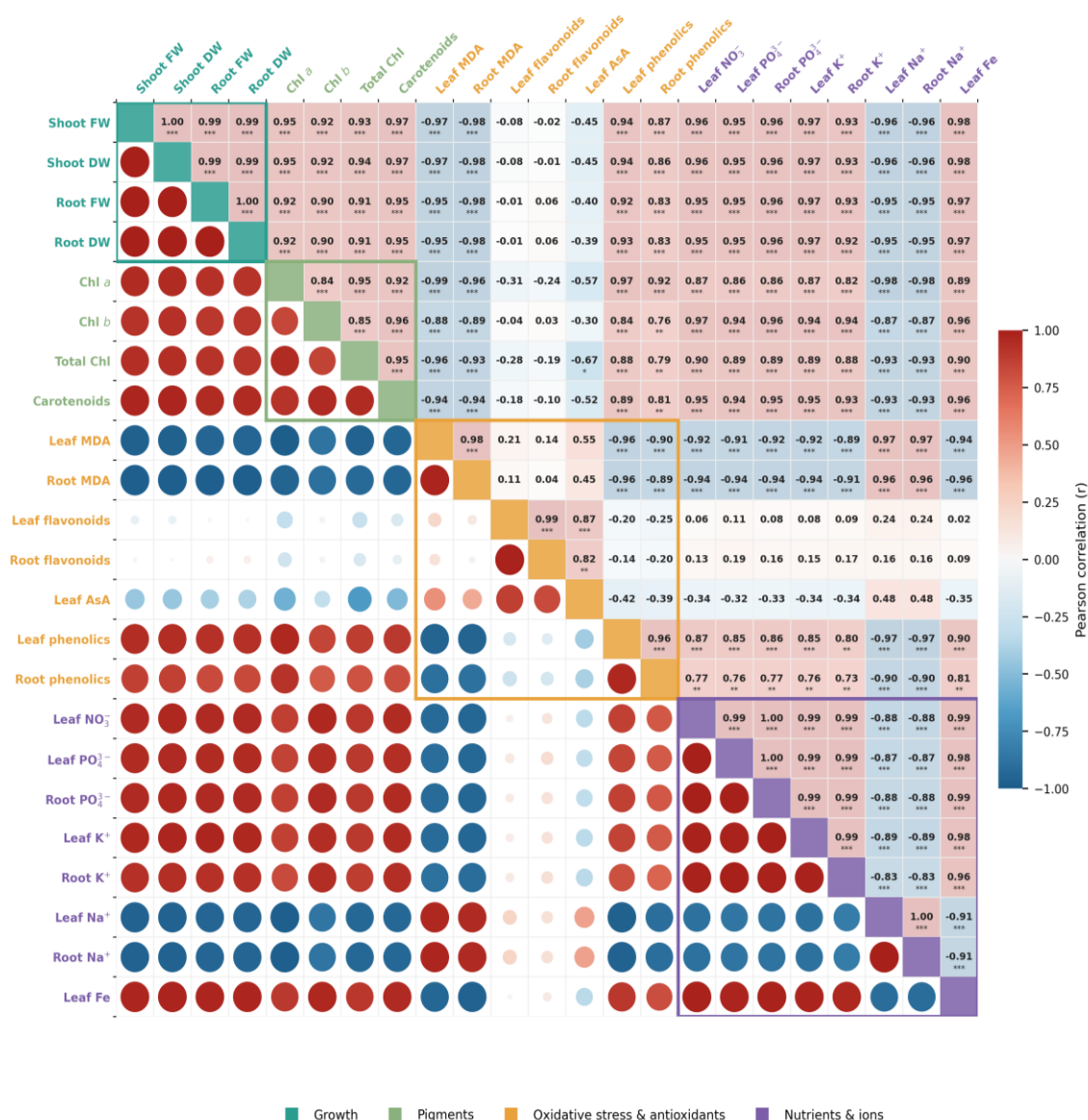


Fig. 5: Correlation among growth, pigment, antioxidant and nutrient traits of onion plants under salinity stress and Fe NP treatment. Pearson correlation matrix of 23 traits calculated from treatment means (3 NaCl levels $\times$ 4 Fe NP concentrations; $n = 12$). Lower triangle: circle size and color show the correlation coefficient (r), with red for positive and blue for negative correlation. Upper triangle: r values with significance (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). Trait groups are color-coded: growth (teal), pigments (green), oxidative stress and antioxidants (orange), and nutrients and ions (purple). MDA, malondialdehyde; AsA, ascorbic acid; Chl, chlorophyll; FW, fresh weight; DW, dry weight.

state (Raphael and Parthasarathi 2026). Consistent with these responses, Hou *et al.* (2024) reported improved antioxidant metabolites and reduced oxidative stress following the use of Fe-based nanomaterials under stressful environments.

Salinity also altered mineral nutrient composition, including nitrate, phosphate, potassium, sodium, and iron (Nawaz *et al.* 2022). Excessive Na⁺ accumulation is a major component of salt toxicity because it competes with

essential nutrients and disrupts ionic balance. K⁺ is particularly important for salt tolerance because it regulates osmotic adjustment, enzyme activation, stomatal movement, and cellular metabolism. In the present study, salinity reduced K⁺ accumulation, while Fe-NP application improved nutrient balance under stress conditions. However, the salinity $\times$ Fe-NP interaction for leaf K⁺ was non-significant, suggesting that Fe-NP application did not significantly modify the effect of salinity on leaf K⁺

accumulation. The significant increase in Fe accumulation following Fe-NP application confirms effective uptake and utilization of foliar-applied nanoparticles. Improved stress tolerance may be mediated by enhanced Fe availability, which may lead to increased activity of antioxidant enzymes, electron transport and formation of chlorophyll (Kreslavski *et al.* 2023). Likewise, better accumulation of nitrate and phosphate following Fe-NP application is indicative of better nutrient uptake and utilization under saline conditions. An improvement in nutrient uptake and ion homeostasis with nanoparticles use has been reported as an important mechanism of salinity tolerance (Jamei *et al.* 2026). The decrease in Na^+ after Fe-NP application suggests that the plants in salinity are better controlled by the flow of Na^+ . Saline condition requires proper balance of Na^+ and K^+ intake for proper growth of plant: sodium high concentration causes disturbance in metabolic activities and causes damages in the cellular structure. Recent research shows that iron-based nanoparticles can control ion homeostasis, improve the efficacy of nutrient assimilation, and improve antioxidant defense systems in salinity (Alsamadany *et al.* 2024). Overall, it was found that use of Fe-NPs in the presence of excessive salt load significantly reduced the physico-biochemical disturbances in the onion plants. Multiple mechanisms were responsible for the positive effect of Fe-NPs such as improved biomass production, preservation of photosynthetic pigments, suppression of oxidative damage, increase of antioxidant metabolites, and regulation of balance of mineral nutrients. Of the applied treatment, 450 ppm Fe-NPs exhibited the highest ameliorative effect, suggesting that optimal application of Fe-NPs could be a favorable approach for enhancing the onion performance in saline environment (Fig. 5).

CONCLUSION

The growth, photosynthetic pigments, antioxidants, and mineral nutrient balance of onion plants were significantly reduced by salinity. The results show that foliar application of Fe-NPs also has a positive effect on alleviating the damage caused by salt stress by enhancing biomass production, maintaining photosynthetic pigments, reducing oxidative stress, and enhancing antioxidant metabolites. Fe-NPs also has the ability to regulate nutrient homeostasis by increasing Fe availability and controlling ionic balance under saline conditions. All treatments exhibited ameliorative activity with the 450 ppm Fe-NPs exhibiting the highest, followed by 350 and 250 ppm treatments. Overall, foliar Fe-NP application is a promising approach to enhance salinity stress tolerance in onion.

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AUTHOR CONTRIBUTIONS

FH, SUR and SN conceived and designed the study; FH, SUR, ZN and AN performed the experiments and analyzed the data; FH wrote the first draft. SN supervised the work and administered the project; all authors reviewed, edited and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

The data will be made available on a fair request to the corresponding author.

ETHICS APPROVAL

Not applicable.

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Funding Insecurity and Organizational Commitment in NGOS and INGOS in Pakistan: A Conceptual Framework of Occupational Stress and Perceived Organizational Support

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ABSTRACT

Background: Non-governmental Organizations (NGOs) and International Non-governmental Organizations (INGOs) may depend on grants, donor commitments, and time-limited projects. When future funding is uncertain, employees can face uncertainty about contract renewal, program continuity, workload and career prospects.

Objectives: This conceptual paper develops a theory-based explanation of how perceived funding insecurity may be associated with occupational stress and organizational commitment in NGOs and INGOS in Pakistan. Major objective is to combine Conservation of Resources theory with Organizational Support Theory and use the Job Demands–Resources perspective as a supporting lens. Occupational stress is proposed as a potential mechanism connecting funding insecurity with commitment, while Perceived Organizational Support (POS) is proposed as a condition that may weaken the negative stress–commitment association.

Methodology: The information for the study was gathered from various online sources including Scopus, Google Scholar, and other online resources especially focusing the social issues. No new data is collected or analysed, and the propositions was treated as theoretical expectations rather than established findings.

Results: Recent research on nonprofit work stress and perceived organizational support suggests that these constructs are relevant to nonprofit settings, while Pakistan-based research has already examined occupational stress among NGO employees. The findings of study do not claim that stress or support has been overlooked altogether; its contribution is the proposed integration of funding insecurity, stress, support, and commitment in one context-sensitive model. Five theoretical propositions are presented for future testing.

Conclusion: This conceptual paper suggests theory-based explanation of the possible relationship between funding insecurity and occupational stress and organizational commitment of NGO and INGO staff in Pakistan. Based on COR theory, it is concluded that lack of funding can be a threat to valuable resources and causes stress. Based on Organizational Support Theory, it is concluded that employees' perception of organizational caring and fair treatment can mitigate the negative relationship between stress and commitment.

INTRODUCTION

Non-governmental Organizations (NGOs) and International Non-governmental Organizations (INGOs) provide support

in areas such as humanitarian aid, community development, advocacy, health services, education, and social protection. Personnel within these organizations often work in challenging settings where program timelines, operational



duties, reporting obligations, and diverse stakeholder demands converge. These demands can be intensified when organizations depend on external grants or project-based funding. Funding uncertainty may affect not only organizational planning but also employees' expectations about employment continuity, compensation, staffing, workload, and future career opportunities.

Occupational stress describes the strain that may arise when perceived work demands exceed the resources available to meet them. Workload, role ambiguity, role conflict, limited control, and inadequate support are established categories of potential work stressors (Cooper and Marshall 1976; Bakker and Demerouti 2007). Organizational commitment in turn is about an employee's connection to an organization. Organizational commitment about how an employee feels about an organization. Three-component framework of Meyer and Allen (1991) distinguishes effective commitment (wanting to stay), continuance commitment (perceiving costs associated with leaving), and normative commitment (feeling an obligation to stay). These dimensions should not be treated as interchangeable: an employee may feel emotionally attached to an NGO's mission while simultaneously worrying about job continuity or may remain because alternative employment is limited.

The supplied manuscript on occupational stress and organizational commitment among NGO and INGO employees in Pakistan provides the context motivating this conceptual development (Butt 2009). However, the manuscript in question reports a cross-sectional study that does not measure funding insecurity or perceived organizational support (POS) as the main variables. Therefore, the statistics presented in that study are not used as evidence for the propositions we develop here. Instead, this paper reframes the issue in theoretical terms: how might funding insecurity influence occupational stress and organizational commitment and under what conditions might organizational support shield employees' commitment?

The question matters because funding insecurity should not be treated as another name for workload or stress. Funding insecurity is an uncertainty that may create or intensify several demands: uncertainty about continued employment, concern about salary or benefits short-term contract renewal, changing project priorities and pressure to do more with fewer resources. These pathways do not claim that every NGO or INGO employee experiences them. The relevance of these pathways will depend on funding arrangements, employment contracts organizational reserves, communication practices and the local labour market.

This paper has three objectives. First to integrate Conservation of Resources theory and Organizational Support theory to explain a pathway from funding insecurity to occupational stress and organizational commitment. Second objective is to propose perceived

support as a contextual condition that may buffer the stress–commitment relationship. Third to identify practical implications, for NGOs, INGOs, donors and future researchers. The intended contribution is a conceptual model, not an empirical test and it does not claim that the proposed relationships have already been demonstrated in Pakistani NGOs.

CONCEPTUAL RESEARCH APPROACH

The approach of this paper is theory-synthesis and model-development. Conceptual research is not just an empirical paper without a results section but rather entails a clear logic in selecting the concepts, articulating their interconnections, and demonstrating how the resulting model contributes to established theory (Jaakkola 2020). Therefore, the paper integrates well-known theories pertaining to resource loss, stress, perceived organizational support, job demands and resources, and multidimensional organizational commitment.

The analysis is done in four stages. The first step is to identify and differentiate the constructs of focus: funding insecurity is defined as a perception of uncertainty concerning organizational funding and its consequences for employment; occupational stress is defined as a potential psychological reaction to demands and threats to resources; organizational commitment is defined as a bond between the employee and the organization that is multidimensional; and POS is defined as a general belief of the employees that the organization values their contributions and cares about them. Second, the use of COR theory is explained to understand the uncertainty of funding that could potentially endanger the valuable resources and add to stress. Third, Organizational Support Theory is applied to explain how positive attachment can be maintained in the case of perceived care, fairness and support. Fourth, these arguments are collated into propositions, and a research agenda can be tested in future studies.

Literature discussion is selective and theoretical and not a systematic review or meta-analysis. It integrates basic theory with pertinent peer-reviewed literature found via targeted searches in scholarly and publisher databases, focusing on those studies that are directly relevant to the areas of nonprofit work stress, perceived organizational support, job insecurity and commitment. In the last few years, recent studies have been cited to bolster the argument, but not as evidence that all of these studies directly test the proposed funding-insecurity model. As the search was not performed as a reproducible systematic search, the paper does not claim to be exhaustive in its description of the size of the evidence base or the novelty of the framework.

For this conceptual paper no participants were recruited, no questionnaire was given and no new data was collected or statistically analyzed. The sample sizes, correlations, reliability coefficients, regression output, and

group comparisons provided in the previous empirical manuscript are not followed through as evidence for the proposed framework.

THEORETICAL FOUNDATIONS

Conservation of Resources Theory

Conservation of Resources theory suggests that people attempt to gain, retain, protect, and increase their resources, and that when these valued resources are threatened, they are lost or not replenished enough after they are invested, stress can occur (Hobfoll 1989). These resources can be things, circumstances, attributes, or energies that people value or that they use to gain things they value. In work, income, job security, time, professional status, predictable work schedules, control, and supportive relationships can serve as resources.

This is an appropriate way to interpret funding insecurity because uncertainty about an organization's financial resources may suggest a potential reduction in resources, even before it happens. Staff can expect to have their contracts up for renewal, pay to be delayed, benefits to be cut, job losses or sudden reallocation of their project duties. The theory doesn't suggest that uncertainty of funding invariably causes stress for all employees. Rather, stress is more likely when an employee feels that there is a potential loss of important resources, and that they don't have credible information, alternatives, or resources available to deal with the stress.

The theory of COR also focuses on the "accumulation of demands". The shortage of funds might result in hiring freezes or workforce cuts, which could increase the work burden, workload, or recovery time for those who are still working. This uncertainty about employment coupled with other demands could result in a process of resource loss. On the other hand, clear communication, fair processes, consistent rulings, and help that is offered practically can aid in conserving resources and reducing uncertainty. These mechanisms constitute the explanation for why funding insecurity could be linked to occupational stress which is provided by the paper.

Organizational Support Theory

Organizational Support Theory is based upon the employees' overall perception of the organization's appreciation for their efforts and concern for their welfare. Eisenberger *et al.* (1986) developed the PS construct based on employees' perceptions of how they were being treated in their organizations. In a later study, it was found that fairness, supervisor support, organizational rewards and favorable job conditions are significant correlates of POS, and that POS is correlated with various outcomes, such as affective commitment, (Rhoades and Eisenberger 2002).

An NGO/INGO setting might include providing staff with a fair deal, keeping them well informed about funding, involving them in a meaningful way, providing reasonable workloads, an accessible supervisor, and endeavoring to keep staff safe when possible. It is not enough to send reassuring messages; managers should make sure that the employees feel supportive by providing them with material information and treating them fairly. Perceived support is dependent on recognizing what the organization is doing and the actions look like they are credible and discretionary.

While the theories of OR Support are not the same as the theory of COR, they are complimentary. COR describes the threat to resources and the stress that occurs because of this threat; Organizational Support Theory describes how employees feel the organization supports them and how this perception may affect attachment and reciprocity. Support can be a resource, but it can also have a relational nature – it can give the message that workers are worth their while and not viewed to an end. This combination enables the framework to apply to the strain pathway and a potential protective condition.

Organizational commitment as a multi-dimensional outcome

Meyer and Allen (1991) defined commitment as effective, continuance, and normative. This is particularly important in cases of uncertainty of employment. Affective commitment can be diminished when insecurity in funding sends the message that the organization is unstable and cannot or will not support the employee. It can impact on commitment to the continuance in other ways: if there is no other job available to them, they could be staying on because it is more expensive for them to leave. Normative commitment can be expressed in terms of loyalty to an organization's mission or responsibility to other beneficiaries and coworkers.

In this way, the overall organizational commitment is considered a general result, while future empirical testing is recommended to take the three dimensions separately. The notion that stresses always leads to the loss of all types of commitment would be incorrect because people can continue to work because they need to or feel obligated to do so. A high level of retention should not be viewed as a sign of good working conditions.

Job Demands–Resources perspective

However, the Job Demands–Resources (JD–R) model offers an alternative approach to categorizing work demands and resources as those that require sustained effort and those that help employees to meet demands and achieve work goals (Bakker and Demerouti, 2007). In this conceptualization, funding insecurity refers to the process of uncertainty that may arise, which can create or

exacerbate job demands (such as uncertainty, workload changes, role conflict), and to organizational support, role clarity, and credible communication as resources.

The JD–R perspective is not a third equal foundation, but rather a supporting perspective. The two main theories explaining resource threat and stress are COR theory and Organizational Support Theory, which explains the relational aspect of organizational care. The JD–R model aids in the operationalization of these concepts in the organization, which can be witnessed and recorded. The theories complement each other in that the combination of them explains more than either theory stands alone.

CRITICAL LITERATURE REVIEW

A contextual antecedent was funding insecurity

In this paper funding insecurity is defined as employees' perceived lack of assurance that an NGO/INGO will get adequate funding for program and employment related commitments. Unlike true funding reduction: If an organization has uncertainty, they do not have a funding reduction confirmed; and, if an organization has a funding reduction, but it is stabilized through reserves, contracts, or communication practices, then employees may not be insecure. This is because the definition of objective funding conditions and employees' perceptions are relevant to the extent to which the uncertainty is perceived and whether employees perceive personal consequences.

There can be several avenues by which funding uncertainty becomes an issue for employees in a project. Firstly, workers can doubt their job or contract security. Second, changes in funding can result in shifts in the emphasis of work and faster deadlines, as well as in the number of employees assigned to a given task. Third, uncertainty can lead to a lack of planning and perceived control, especially if information is late or inconsistent for employees. These are plausible mechanisms, which cannot be put forward as a characteristic measured in the provided sample or as a universal feature of all NGOs/INGOs.

Funding insecurity is different from Job insecurity. Funding insecurity is the feeling that it is difficult for the organization to secure funding, job insecurity is the feeling that the job the employee has may not last or may not include the same features. The ideas can be linked, but not synonymous: An organization can have a diversified reserve of funds, but an employee may still be concerned about renewal of his/her contract; A temporary revenue shortage can be met without immediate layoffs. Funding insecurity is considered an upstream contextual perception, while job insecurity is one possible way that employees understand funding insecurity, rather than assuming the two are synonymous.

Insecurity of funds can also have other effects than stress. It can influence staff's perceptions of the reliability, fairness and future of the organization. When an

organization reacts to uncertainty by making clear decisions and using fair processes, staff can see it as being responsible while constrained. Lack of communication or arbitrary decision-making may be interpreted by employees as uncertainty in management or lack of interest. The external funding context then can be felt differently in each organization.

Occupational stress and commitment

Work-stress models have focused on job demands, role-related stressors, organizational factors, and interpersonal stressors in the workplace as sources of stress (Cooper and Marshall 1976). The JD–R model also suggests that high demands may have a negative impact on well-being, especially if there is a lack of resources (Bakker and Demerouti, 2007). A plausible stress pathway in NGOs and INGOs would be concerns about maintaining employment, about increased demands on the job, role ambiguity, and conflicts between program demands and resource availability.

This relationship is not just the background in the nonprofit context. Using the data from the European Working Conditions Survey, Palumbo *et al.* (2025) examined the relationship between time-related stress and work climate, with the results indicating that the relationship was mediated by work–life conflict and work engagement, not just through work–life conflict alone. The benefit this provides in the context of the present argument is that it warns against presupposing that stress will always equate with a corresponding decrease in the organization's attitudes. Cheema *et al.* (2021) in Pakistan used Conservation of Resources theory to explore the occupational stress and employee engagement for the employees of NGOs. The study does not establish the proposed pathway of funding insecurity – stress – commitment in Pakistani NGOs, but it does confirm that the issue of occupational stress in Pakistani NGOs is already a research topic.

Stress can be correlated with lower levels of organizational commitment in a few ways. Over time, this can decrease the amount of "energy" employees can dedicate to being part of the organization and make positive work experiences more difficult. Unresolved stressors can also be seen as a lack of organization value for the employee. Such interpretations are especially important for affective commitment, which is related to emotions and identification (Meyer and Allen 1991).

The results from a wider employee environment are also supportive of the assumption of insecurity and strain as potential antecedents of commitment. For instance, an association between job insecurity and burnout, and job insecurity and organizational commitment were found to be negative by Anand *et al.* (2023) The study is not an NGO-specific study, and job insecurity is not the same as funding insecurity, and should be considered as add-on evidence,

not as support for the propositions of this paper. It's an important difference, because the conceptual argument must be evaluated with grants before a causal conclusion can be drawn in any sector.

But it doesn't have to be one-to-one or one-to-many. Employees can still be committed to a social mission despite the demanding situation; some are willing to take on additional work because they are committed, and this can place additional strain. When there are limited employment opportunities, commitment to continue may remain unchanged or even increase. The possibilities warn against the view of the stress–commitment relationship as a universal causal law. The theoretical suggestion, or concept, is that occupational stress could be a mechanism that bridges the funding insecurity–commitment relationship, and the size and shape of this relationship is empirical.

POS as a contextual resource

POS can be significant because it is a cue for employees on how valued their work and welfare are to their organization. The evidence that was reviewed by Rhoades and Eisenberger (2002) is consistent with the positive relationship between POS and treatment, equity, supervisor support, and affective commitment. Supportive practices will not cure the underlying funding issue in an organization with limited funds. They can still, however, enlighten workers on decision making, provide support and make them feel valued during uncertainty. Of relevance is the synthesis by Prysmakova and Lallatin (2023) about POS in public and nonprofit organizations. In their review of 57 studies, they reported positive outcomes of POS such as commitment, intention to stay, wellbeing and reduced stress, and noted the geographical and organizational limitations of the underpinning studies. This lends credence to the importance of POS in the nonprofit context, but it does not provide evidence that POS does buffer the impact of occupational stress on commitment for Pakistani NGOs. The moderation proposition proposed here is thus a theoretical question for future research, rather than a conclusion. An important difference is between instrumental and symbolic support. Instrumental support involves pragmatic measures like reasonable workload, prompt contract notification, job transition support (when appropriate) and leave support. Symbolic support is respectful communication, the recognition of efforts, consulting, and transparent explanations. While symbolic actions cannot fill the place of wages or job security, actions without respectful communication can equally fail to build a good feeling of support. The framework thus does not see POS as a managerial message, but rather as an employee perception about the way the organization treats individuals. There are two ways in which POS could influence the model. It could be directly connected with commitment as employees who feel valued could be more

emotionally attached to the organization. May also moderate the stress–commitment relationship: a negative relationship between stress and commitment can be reduced if an employee has a positive perception of the organization's efforts to support him or her during the stressful time. The present model focuses on the buffering pathway as well as the possibility of a direct pathway between the POS and commitment.

Synthesis and research gap

The theoretical literature provides separate explanations for resource threat and stress (Hobfoll 1989), the meaning and consequences of POS (Eisenberger *et al.* 1986; Rhoades and Eisenberger 2002), the organization of job demands and resources (Bakker and Demerouti, 2007), and the different bases of commitment (Meyer and Allen 1991). Conceptual opportunity is to bring together these explanations around funding insecurity as a contextual condition that is relevant to project- and grant-dependent organizations.

The proposed gap is not that occupational stress, organizational commitment, or POS have never been studied in Pakistan or in NGOs. Occupational stress among NGO workers has been studied in Pakistan (Cheema *et al.* 2021), and in the non-profit sector, POS has been associated with commitment and well-being (Prysmakova and Lallatin 2023). Further, time-related stress and work climate have been explored in recent studies by non-profit organizations (Palumbo *et al.* 2025) and organizational commitment has been linked to job insecurity and burnout among employees (Anand *et al.* 2023). A more defensible conceptual opportunity is to merge these intertwined yet separate themes in the context of perceived funding insecurity with occupational stress as a possible mechanism and POS as a possible boundary condition. This exact mix of ingredients will need to be established by a documented systematic search before submission if it is not the one used in Pakistan.

The synthesis also brings three issues that are unresolved to the fore. Insecurity is a different issue from workload or job insecurity. Second, commitment must be considered in all its dimensions, and not as a monolithic attitude. Third, a protective role of support in material security may not be fully realized, as its effect will be limited to those who believe it and feel rewarded, and depend on the resources the organization can deliver. These differences inform the following framework and propositions.

CONCEPTUAL FRAMEWORK AND THEORETICAL PROPOSITIONS

Proposed framework

The proposed model considers funding insecurity as a

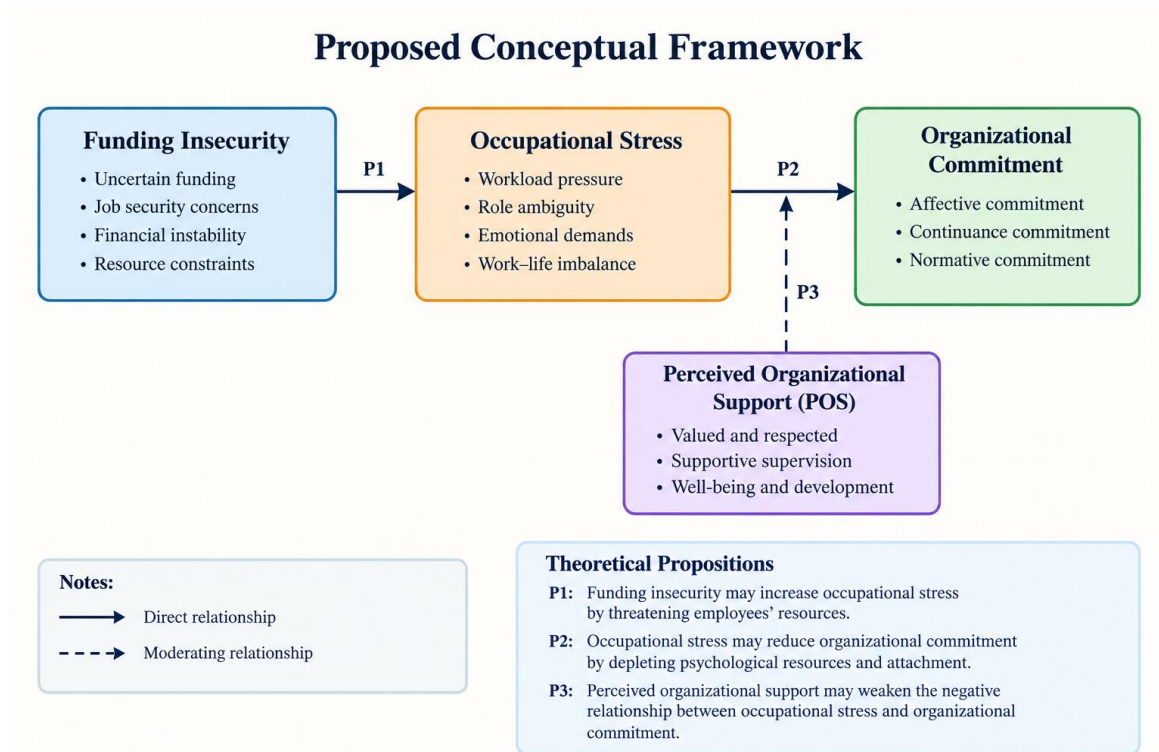


Fig. 1: Proposed conceptual framework linking funding insecurity, occupational stress, organizational commitment, and perceived organizational support

predictor of organizational commitment and occupational stress (Fig. 1). Funding insecurity may be related to commitment, in part, because it threatens resources and increases strain. Occupational stress is proposed as a possible mediator. The study indicates that POS moderates the relationship between occupational stress and organizational commitment. Thus, the negative relationship between stress and commitment will likely be weaker when POS is higher than when it is lower. This is what we would expect theoretically, not empirically.

Proposition 1: Funding insecurity and occupational stress

Perceived funding insecurity will be positively related to occupational stress for NGO and INGO employees. This is in line with the COR theory rationale that uncertainty about the continuity of funding may threaten valued resources such as income, continuity of employment, predictability, and control (Hobfoll 1989). Uncertainty may itself call for ongoing attention and coping effort in situations where employees expect job loss or lack of resources. Funding insecurity may also lead to organizational responses, such as redistribution of workload and re-prioritization. The proposition predicts an association rather than an inevitable effect because contract protections, reserves, alternative employees, and credible communication may alter employees' appraisals.

Proposition 2: Occupational stress and organizational commitment

Organizational commitment, in the first place, affective commitment, will be negatively associated with occupational stress. The cumulative effect of stress could diminish employees' abilities to feel connected, trusted, and good with the organization. When employees feel that their demands for excessive demands are not met, their emotional attachment can be reduced. This forecast is like the separation between affective commitment and reasons other than feeling love for an organization (Meyer and Allen, 1991). A negative relationship may be weaker, null or even reversed for continuance and normative commitment as employees may choose to remain because of perceived exit costs or obligation, even if they are strained.

Proposition 3: Occupational stress as a mediator

There will be a mediated relationship between perceived funding insecurity and organizational commitment via the mediating role of occupational stress. Higher ratings of perceived funding insecurity related to higher ratings of occupational stress, is related to lower levels of organizational commitment. This proposition is not just a statement of correlation between two variables, but also of

mechanism. Funding insecurity may put resources at risk, increase strain, and increase an organization's attachment problem. Cross-sectional correlations should not be taken as evidence for mediation. Evidence of the proposed sequence would be strengthened if temporally separated measures or a longitudinal design were used, and with appropriate controls and direct testing of indirect effects.

Proposition 4: POS as a moderator

The POS would buffer the negative relationship between occupational stress and organizational commitment, thereby reducing the negative impact when POS is high. According to Organizational Support Theory, when a person feels that an organization cares for them and treats them fairly, they feel valued by the organization (Eisenberger *et al.* 1986; Rhoades and Eisenberger 2002). In crisis situations high POS can create a sense of trust and emotional bond, as employees feel not to be in the situation alone. Low POS can exacerbate negative stress perceptions, particularly when team members feel managers don't pay attention to their input or are not being fair. It is not a proposition about the absence of material consequences of unstable funding; it is a proposition about a buffering effect.

Proposition 5: Funding insecurity, POS, and commitment

This indirect negative relationship between funding insecurity and organizational commitment via occupational stress will be weaker if the level of POS is high. This is an indirect effect proposition that is conditional and a combination of the previous arguments. Occupational stress when high might be less associated with commitment, and thus the indirect relationship between funding insecurity via stress to commitment may be less pronounced. The proposition goes beyond just considering stress as a potential mechanism and adds to the question of the level of the mechanism based on employee perceptions of organizational treatment. Empirical tests of the proposed size and reliability of moderated mediation are needed before any conclusions can be drawn.

BUILD BOUNDARIES, FUTURE OPERATIONALIZATION

Future researchers should clearly define funding insecurity and separate employee perceptions of funding insecurity from objective measures like the amount of restricted funding, the length of grant contracts, the length of time grants are funded, or whether the budget is confirmed to be reduced. To prevent construct overlaps, occupational stress should be assessed independent of funding insecurity and job insecurity. It is recommended to measure POS as an employee's perception of caring and valuing from the organization, while organizational commitment should be

analyses in three dimensions namely affective, continuance, and normative. Other potentially relevant contextual variables such as organizational type, role, tenure, employment contract, income security, and work location should also be considered in the study design. A future test may involve several organizations and/or multiple time points. In the same manner, Funding insecurity might be measured at an initial time, stress later, commitment at a later time and POS as a contextual condition. Employee perceptions could be correlated with information about the funding or contract level in an organization. This type of design would not automatically prove causality but would give more temporal evidence than a one-shot questionnaire.

THEORETICAL CONTRIBUTIONS

First, the paper has redefined funding insecurity as a contextual antecedent of occupational stress as a reaction to the immediate demands of the job rather than only because of immediate job demands. This distinction highlights uncertainty over resources and programmers' continuity that can impact on employees prior to any confirmation of budget reduction. Second, the paper pulls together COR theory and Organizational Support Theory to discuss various aspects of the proposed process. Theories of funding insecurity (COR theory) and of maintaining attachment (Organizational Support theory) help to explain why funding insecurity can be appraised as a threat to valued resources and can be a source of stress and why perceived care and fair treatment can sustain attachment. There is no decorative integration: each theory is used to answer a different explanatory question. Third, the model also suggests process and boundary conditions by positing occupational stress as a potential mediator and POS as a potential moderator. This is a more descriptive document than a document that simply lists familiar variables side by side. It also generates propositions which can be disproved or improved by observation. Fourth, the framework provides a differentiation of dimensions of organizational commitment. Affective commitment might be particularly vulnerable to employees' perceptions of stress and support, and continuance and normative commitment may stem from different reasons for staying. This distinction warns managers and researchers not to take retention as a sign of a supportive or healthy workplace. Finally, the framework is placed in the NGO/INGO context without assuming that all NGOs or INGOs have the same funding and employment model. It has a degree of contextual relevance that is a theoretical proposition to be investigated, not a claim of generalizability across a sector. The contribution should be assessed on the basis of whether the integrated model is found to be explanatory over some of the other existing accounts of it after a literature review and testing.

PRACTICAL IMPLICATIONS FOR NGO MANAGERS AND FUNDERS

Implications for NGO/INGO managers

Managers need to think about funding uncertainty as an organizational planning issue and a potential employee well-being issue. Where information can be shared, updates should be timely, clear, and honest about what is known, what remains uncertain, and when decisions are expected. It's important not to use unsupported promises: credibility will be more important than any short-term promise that is later shown to be false.

Alternatively, managers may check workload and role allocations during funding changes. Responsibilities should be prioritized in a transparent manner, not transferred in an informal way without discussion to other employees, if there are insufficient vacancies or projects are reduced. Role clarity, role descriptions, reasonable timeframes, and easily available avenues of escalation can minimize confusion and conflict that is unnecessary. These are suggestions for management, and not interventions that have been proven by this conceptual paper.

Support needs to be relational as well as practical. Reactions can involve advance notification about contract decisions, consistent treatment, timely compensation, equitable access to leave, supervisor check-ins, employee consultation, career development referrals and respectful transition support when jobs cannot be maintained, depending on the resources of the organization and employment arrangements that apply. Employees' dedication to a social mission does not give managers an excuse to accept unsafe workloads or high-risk work.

Implications for donors and funders

Funders might look at whether the timing of money and the paperwork needed add confusion for the groups that use the funds and their workers. If funders set up payment dates give quick updates about renewals give realistic project deadlines and keep paperwork reasonable those groups can better arrange staff and tasks. Funders who offer multi-year or more flexible funding, when suitable can also let those groups plan steadier jobs. These implications are proposals, for consideration rather than claims that a particular funding model necessarily improves commitment.

Implications for policymakers and sector networks

Sector networks and policymakers play a crucial role in promoting transparent employment practices and sharing practical advice on staff well-being, especially in organizations that rely on grants. Practical guidance should address clear communication about contracts, regular workload checks, safe ways for staff to report concerns, and fair treatment during organizational

changes. It's important to make a clear distinction between dedication to the mission and expecting staff to make endless personal sacrifices. Any guidance needs to fit local labor laws, the organization's resources, and specific program needs.

Avoiding the individualization of structural problems

One of the key messages is that stress management shouldn't be restricted to in-person resiliency training. Individual coping interventions are not going to replace organizational action when uncertainty is caused by funding cycles, staffing decisions or conflicting demands. The proposed framework focuses on context that creates threats to resources but also on the support that can be expected by employees.

LIMITATIONS AND FUTURE RESEARCH

This is a conceptual paper that does not contain any new empirical information. Its propositions are not yet empirically tested and are only theoretical reasons for beliefs. Some variables in the model may not be included that are relevant for the phenomenon, e.g. leadership, psychological contract breach, job insecurity, trust, perceived fairness, employment alternatives, organizational reserves or individual coping resources. Future research will explore whether these variables contribute to understanding and whether there is a conceptual overlap between funding insecurity or POS.

Literature synthesis is selective, not systematic. Prior to the submission to a journal, the authors should do a searchable and repeatable literature search on available relevant databases and regional journals and then review literature on NGOs/INGOs, funding uncertainty, stress, commitment, and organizational support in Pakistan and similar settings. The novelty claim needs to be adjusted based on the search conducted.

The framework also assumes that funding insecurity can be meaningfully separated from objective funding conditions and job insecurity. It may be necessary to develop a new measure to reflect uncertainty about funding and not just the fear of being laid off from one's position. Other factors that could be included in future studies if available and ethically sound are grant cycles, contract length, funding focus, and disbursement delays.

Time ordering and alternative explanations should be considered when considering empirical tests. Longitudinal research might be able to test out if funding insecurity leads to changes in stress level and if stress leads to changes in commitment. Multilevel designs may be helpful because funding conditions and management practices are likely to be at an organizational or project level, while stress and POS are likely to be measured at the employee level. The commitment dimensions should be tested separately, and it is important to provide transparency on measurement

quality, effect size, confidence intervals, missing data procedures and robustness checks.

Finally, the framework does not simply mean that all NGOs and INGOs are the same. The relevance of proposed relationships may be affected by the nature of organization, its mission, its donors, its geographical context, its employment structure and its role. Comparisons might be made between local NGOs and international organizations, permanent project staff, or field and office staff.

CONCLUSION

This conceptual paper suggests theory-based explanation of the possible relationship between funding insecurity and occupational stress and organizational commitment of NGO and INGO staff in Pakistan. It is based on COR theory and suggests that lack of funding can be a threat to valuable resources and cause stress. It is based on Organizational Support Theory, which suggests that employees' perception of organizational caring and fair treatment can mitigate the negative relationship between stress and commitment. The JD–R approach offers a complementary approach to differentiate work demands from resources. Five propositions are proposed as the expected relationships: funding insecurity may be positively associated with occupational stress, organizational commitment (specifically affective) may be negatively associated with stress, stress may mediate the funding insecurity–commitment relationship, POS may moderate the stress–commitment relationship, and POS may reduce the indirect negative association between funding insecurity and commitment through stress. These propositions are not findings and should not be called statistically supported. The key contribution of the paper is the creation of a context-sensitive integrated model of employee commitment and uncertainty of funding of a resource threat and perceived organizational support. The framework provides a foundation for future longitudinal and multilevel research and provides a reminder to NGO/INGO managers and funders to think about how to communicate transparently, how to conduct fair procedures, how to manage workloads and how to ensure the credibility of support. A systematic review and empirical testing should be used to assess its novelty and applicability.

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AUTHOR CONTRIBUTIONS

Both authors contributed equally to this work

CONFLICT OF INTEREST

We, the authors declare no conflict of interest

DATA AVAILABILITY

Not applicable

ETHICS APPROVAL

Not applicable

FUNDING SOURCE

Not applicable

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A 67-Year-Old Male with Hypercalcaemia and Giant Parathyroid Adenoma

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ABSTRACT

Background: Primary hyperparathyroidism (PHPT) is an endocrine disorder in which the parathyroid glands secrete excess parathyroid hormone (PTH), most often because of a single parathyroid adenoma. Giant parathyroid adenomas (GPAs) are rare and can cause severe hypercalcaemia.

Objective: To highlight the diagnostic challenges and management of severe symptomatic primary hyperparathyroidism caused by a large parathyroid adenoma in an elderly patient, emphasizing the role of biochemical and imaging investigations, surgical excision with intraoperative parathyroid hormone monitoring, and postoperative calcium management to prevent hungry bone syndrome.

Methodology: The pot experiment was carried out in 3×4 factorial completely randomized design (3 replicates) with salinity: 0, 150 and 200 mM NaCl and Fe-NP foliar application: 0, 250, 350 and 450 ppm. The growth parameters, photosynthetic pigments, oxidative stress parameters, antioxidant metabolites and mineral nutrients were measured by standard procedures.

Results: After hydration and bisphosphonate therapy, the adenoma was surgically excised with intraoperative PTH monitoring. Serum calcium and renal function returned to normal after surgery, and the patient was discharged on calcium and vitamin D supplements to prevent hungry bone syndrome.

Conclusion: Early diagnosis of PHPT caused by a giant parathyroid adenoma, using PTH measurement and imaging, followed by surgical excision, can prevent further bone and kidney damage.

INTRODUCTION

Primary hyperparathyroidism (PHPT) is a common endocrine disorder in which the parathyroid glands secrete excess parathyroid hormone (PTH). It is most often caused by a single parathyroid adenoma (Al-Hassan *et al.* 2019), a benign tumour of one of the parathyroid glands, which lie in the neck behind the thyroid gland. PTH regulates calcium homeostasis. Excess PTH raises serum calcium by stimulating osteoclast activity and suppressing osteoblast activity in bone, and the resulting hypercalcaemia produces the clinical features of the disease (Mahmodlou *et al.* 2022). Most parathyroid adenomas are small, usually weighing less than 1 g (Narla *et al.* 2020), and cause relatively few

problems. Larger adenomas are more difficult to diagnose and to treat (Mahmodlou *et al.* 2022).

A giant parathyroid adenoma (GPA) is a rare, benign tumour that is usually defined by a weight above 3.5 g (Al-Hassan *et al.* 2019; Mahmodlou *et al.* 2022). Fewer than 1% of cases are of this type, yet a GPA is a clinically important cause of marked PHPT. Whereas sporadic adenomas are usually smaller than 2 cm, GPAs can be associated with very high PTH and calcium levels and with severe systemic complications, including osteitis fibrosa cystica, renal dysfunction and neuropsychiatric manifestations. Biochemically, a GPA can resemble parathyroid carcinoma, but microscopy shows no invasion of the surrounding tissue (Houas *et al.* 2023). Diagnosis relies on PTH measurement,

ultrasonography and sestamibi scintigraphy, and surgical resection, which is usually curative, is the only definitive treatment. Delayed treatment can cause permanent bone and kidney damage. After surgery, hungry bone syndrome may occur, in which the bones take up large amounts of calcium and cause hypocalcaemia, so postoperative calcium monitoring is mandatory. Here we report a patient with symptomatic hypercalcaemia (fatigue, bone pain and a history of kidney stones) and an imaging-documented GPA. The aim is to highlight the diagnostic and therapeutic approach and the importance of recognising disease early.

CASE PRESENTATION

Clinical history and examination

A 67-year-old retired teacher presented to Sir Ganga Ram Hospital, Lahore, with severe fatigue that did not improve

with rest. He also reported bone pain, with no history of injury or arthritis, and a four-month history of intermittent vertigo described as a spinning sensation, without ear pain or hearing loss. Vertigo is a nonspecific symptom with many possible causes (Kim 2021). On further questioning, he reported constipation and frequent urination, and he had a previous history of kidney stones. The fatigue and bone pain had been present for about a year and were gradually worsening. This combination of symptoms raised the suspicion of hypercalcaemia.

Laboratory investigations

Laboratory tests showed severe hypercalcaemia, with a serum calcium of 13.1 mg/dL, and a markedly raised PTH of 537.5 pg/mL (Table 1; Fig 1–3). Serum phosphate was low at 1.5 mg/dL, consistent with the phosphaturic action of PTH, which reduces renal phosphate reabsorption.

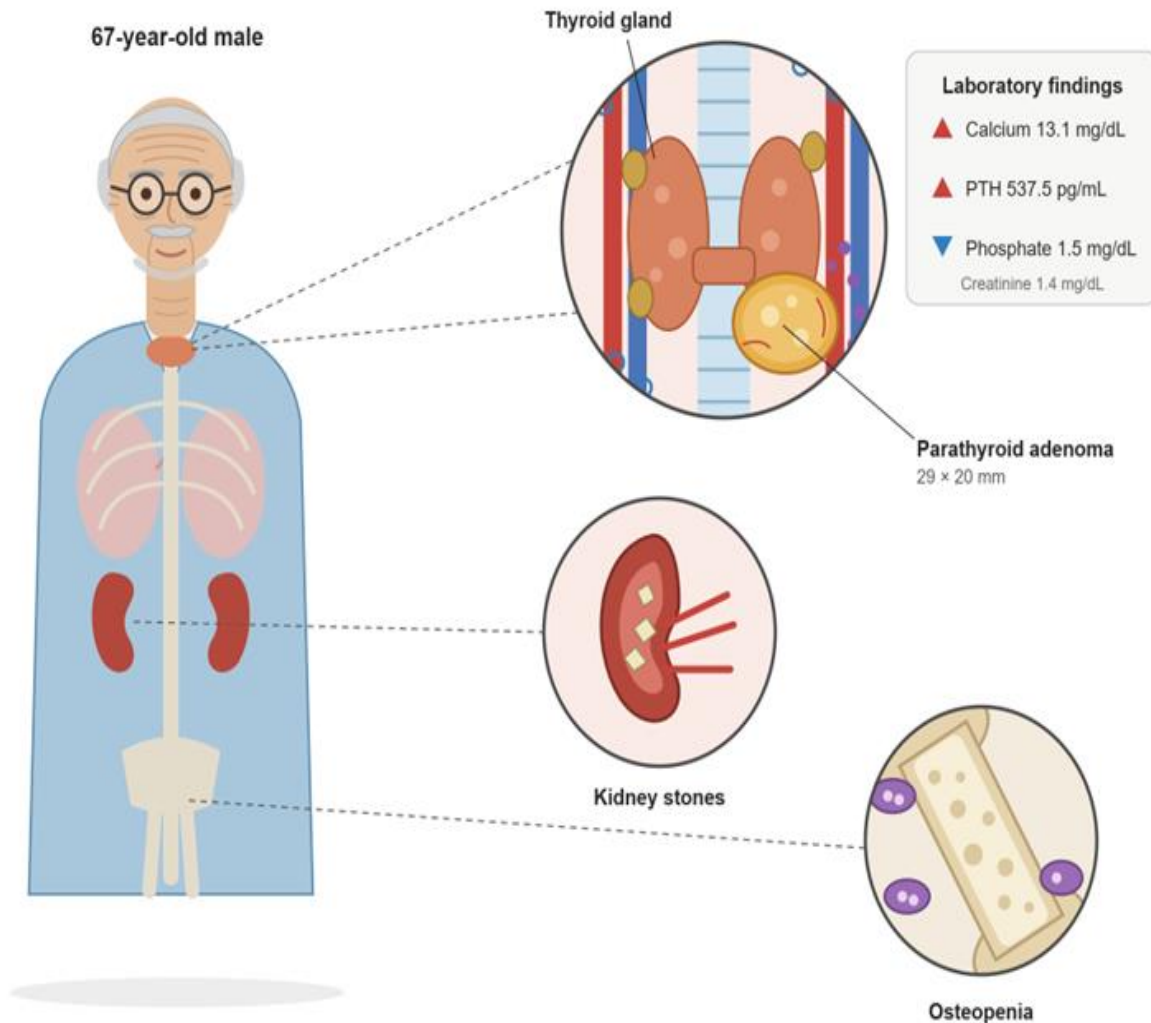
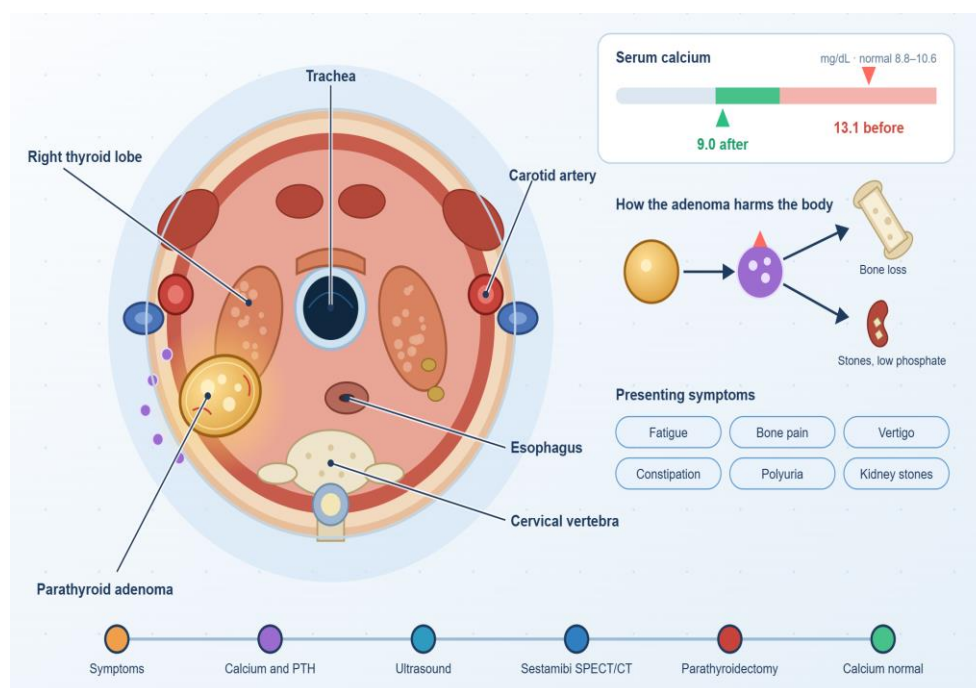


Fig. 1: Case representation

Table 1: Biochemical findings before and after surgery

Parameter	Pre-op	Post-op	Reference range
Serum calcium (mg/dL)	13.1	9.0	8.8–10.6
Serum phosphorus (mg/dL)	1.5	4.4	2.5–4.5
Alkaline phosphatase (U/L)	150	113	30–120
Serum creatinine (mg/dL)	1.4	0.9	0.67–1.17
Blood urea (mg/dL)	38	36	17–43
Parathyroid hormone (pg/mL)	537.5	NR	NR

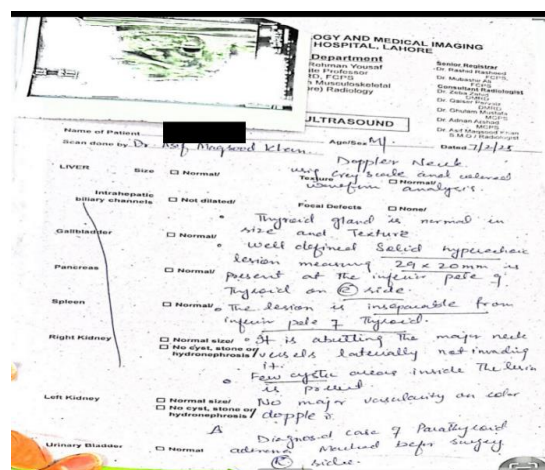
**Fig. 2:** Axial neck view of a 67-year-old man showing a giant parathyroid adenoma behind the right thyroid lobe, its effects on bone and kidney, and the clinical course

Pathology Lab Sir Ganga Ram Hospital Lahore Queens Road Lahore Ph # 9200572 - 80, Ext. 3054			
Patient Name:	Gender:	Lab No:	10473
Age:		Report Date:	09-Feb-2025 1:15 am
Ward / OPD:	MS1		
Test Name	Result	Unit	Normal Range
Blood Urea	38	mg/dL	17 - 43
Serum Creatinine	1.4	mg/dL	0.67 - 1.17
Bilirubin	18	mg/dL	08 - 20
Uric Acid	3.9	mg/dL	M: 3.5 - 7.2 F: 3.5 - 6.0
Bilirubin Total	0.6	mg/dL	Upto 1.2
SGPT	29	U/L	M: up to 50 F: up to 35
SGOT	27	U/L	M: up to 50 F: up to 35
Alk. Phosphatase	150	U/L	30 - 120
LDH	200	U/L	Upto 240
S. Calcium	13.1	mg/dL	8.8 - 10.6
S. Phosphorus	1.5 (N)	mg/dL	2.5 - 4.5
Magnesium	2.0	mg/dL	1.8 - 2.5
Sodium	139	mmol/L	135 - 150
Potassium	6.3	mmol/L	3.5 - 5.5
Glucose	105	mmol/L	90 - 105
Hbs Ag	NON REACTIVE		
Anti HCV	NON REACTIVE		
CRP	0.71	mg/L	Less Than 10.0

Electronically verified report. No signature required

Dr. M. Riaz Hussain
Consultant Pathologist

SARDAR SANCHI SINGH
Lab Technician

Fig. 3: Pre-operative routine biochemistry report of the patient (patient identifiers masked)**Fig 4:** Neck ultrasonography report showing a 29 × 20 mm solid hyperechoic lesion at the inferior pole of the right thyroid lobe (patient name masked)

Institute of Nuclear Medicine and Oncology

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Phone: 042-99231064 - 68 Fax: 042-99230778 Email: info@innmolaech.gov.pk

PRN: 002520/25 Age: 67 Year(s) Gender: Male Entry Date: 22-Jan-2025

City: Lahore

PARATHYROID SPECT-CT

Clinical Features:
Serum PTH 567 pg/ml

Procedure:
Parathyroid scanning was done employing Dual Phase 99mTc-MIBI scintigraphy. 20mCi of tracer was injected and anterior static imaging of neck was acquired at 15 minutes, 01 hour and then at 2 hours along with SPECT/ CT of the neck region.

Findings:
The early imaging at 15 min shows radiotracer uptake in both lobes of the thyroid with a focal area of increased radiotracer uptake in the region of lower pole of right lobe.
Imaging at 1 hr shows partial tracer washout from the thyroid gland with retention of radiotracer activity in the lower pole of right lobe of thyroid.
Delayed imaging at 2 hrs shows almost complete tracer washout from the thyroid gland. Focal area of activity retention still persists in the lower pole of right thyroid gland.

Co-relative SPECT/ CT of the neck: It shows hypodense tracer avid focus measuring 17mm x 13mm outside the thyroid gland posterior to right lobe of thyroid -highly suggestive of parathyroid adenoma

Opinion:
Scan evidence of parathyroid adenoma posterior to right lobe of thyroid gland

Correlation with MRI neck is suggested

Reviewed By

Dr. Tahira Yasmeen
Reporting Doctor

Printed On: 2025-01-23 10:56:19

Fig. 5: Parathyroid SPECT/CT report (dual-phase 99mTc-sestamibi scintigraphy) suggesting a parathyroid adenoma posterior to the right thyroid lobe (patient identifiers masked).

Imaging

Neck ultrasonography showed a well-defined, solid, hyperechoic lesion measuring 29 × 20 mm at the inferior pole of the right thyroid lobe (Fig. 2). The lesion contained a few cystic areas and showed no major vascularity on colour Doppler. Dual-phase 99mTc-sestamibi scintigraphy with SPECT/CT showed focal tracer retention in the lower pole of the right thyroid lobe that persisted on delayed images, confirming a parathyroid adenoma (Figure 3). DEXA scanning showed osteopenia, consistent with chronic PTH-mediated bone resorption (Pandya *et al.* 2024). Raised PTH increases osteoclast activity, which causes loss of both cortical and trabecular bone; this explains the bone pain and the increased risk of fracture.

Management and outcome

The patient had symptomatic hypercalcaemia, with features such as weakness and dehydration, and surgery was therefore advised. Before surgery, intravenous fluids were given to correct dehydration and control serum calcium, together with a bisphosphonate to lower serum calcium by limiting bone resorption. The adenoma was removed by surgical excision, with intraoperative monitoring of PTH. After the operation, serum calcium (9.0 mg/dL), phosphate (4.4 mg/dL), alkaline phosphatase (113 U/L) and creatinine (0.9 mg/dL) were within the reference ranges (Table 1; Fig. 6). The patient was discharged on calcium and vitamin D supplements to prevent hungry bone syndrome. Histopathology and weight of the excised specimen

Pathology Lab Sir Ganga Ram Hospital Lahore
Queens Road Lahore Ph # 9200572 - 80, Ext. 3054

Patient Name: [REDACTED]		Gender: [REDACTED]
Age: [REDACTED]		Lab No: 10622
Ward / OPD: MS1		Report Date: 09-Feb-2025 11:06 pm

Test Name	Result	Unit	Normal Range
Bilirubin Total	36	mg/dl	17 - 43
Serum Creatinine	0.9	mg/dl	0.67 - 1.17
Uric Acid	17	mg/dl	08 - 20
Bilirubin Total	3.3	mg/dl	M: 3.5 - 7.2 F: 3.5 - 6.0
SGPT	0.8	mg/dl	Upto 1.2
SGOT	65	U/l	M: up to 50 F: up to 35
Alk. Phosphatase	81	U/l	M: up to 50 F: up to 35
CPK	113	U/l	30 - 120
LDH	83	U/l	M: up to 170 F: up to 145
S. Calcium	253	U/l	Upto 248
S. Phosphorus	9.0	mg/dl	8.8 - 10.6
Magnesium	4.4	mg/dl	2.5 - 4.5
Sodium	2.0	mg/dl	1.8 - 2.5
Potassium	142	mmol/l	135 - 150
Chloride	4.2	mmol/l	3.5 - 5.5
Hbs Ag	104	mmol/L	90 - 105
Anti HCV	NON REACTIVE		
CRP	NON REACTIVE		
	3.56	mg/l	Less Than 10.0

Electronically verified report. No signature(s) required

These tests are being performed on the test of an of Fully Automated Immunoassay Analyzer AU 680 Beckman Coulter
USA. This system is based on Enhanced Chemiluminescence Immunoassay Technology for better sensitivity and accuracy
of results.
The result can not be compared with any other laboratory as every lab has its own procedures and quality control.

Dr. M. Riaz Hussain Consultant Pathologist	SANDAR SANTOKH SINGH Lab Technologist	Lab Technician
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Fig. 6: Post-operative routine biochemistry report of the patient (patient identifiers masked).

DISCUSSION

This case shows a severe presentation of PHPT caused by a large parathyroid adenoma. Three points deserve emphasis: the need for timely diagnosis in patients with nonspecific symptoms such as fatigue, bone pain and vertigo; the central role of PTH measurement and imaging (ultrasonography and sestamibi scintigraphy) in localising adenoma; and the role of surgery as a definitive therapy, with medical management reserved for patients who cannot undergo surgery.

The symptoms of our patient were common and nonspecific. Fatigue, bone pain and vertigo occurred daily, together with other vague complaints, and all were ultimately explained by PHPT, in which the parathyroid

gland releases excess PTH. Giant adenomas are uncommon, but when they occur the symptoms are usually severe and serum calcium reaches high levels (Singh *et al.* 2022). PTH measurement, ultrasonography and sestamibi scintigraphy were used for diagnosis. The optimal treatment for parathyroid adenoma is parathyroidectomy. However, if this is not possible then medical management can be used including calcimimetics and bisphosphonates (Leere *et al.*, 2017). The patient's serum calcium and renal function were normal following surgery, which shows a positive response to the surgical treatment. Early identification of clinical symptoms and timely management is vital to prevent long term complications from severe hyperparathyroidism. Monitoring serum calcium levels after surgery can help

identify and manage any complications, such as hungry bone syndrome.

Follow-up

Renal function and bone density will improve over a period of 1-2 years. Regular follow up is required to monitor for any recurrence and hungry bone syndrome.

CONCLUSION

A giant parathyroid adenoma is a rare but significant cause of primary hyperparathyroidism and can present with non-specific symptoms such as fatigue, vertigo, bone pain, polyuria and constipation. Serum calcium, phosphate and PTH levels alongside ultrasound and sestamibi scans can help make a quick diagnosis and localise the lesion. Surgery is the definitive treatment. Early diagnosis can prevent permanent kidney and bone damage. Careful monitoring and supplementation of calcium can also help to avoid hungry bone syndrome.

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AUTHOR CONTRIBUTIONS

FR and NA conceived the case report and supervised the work. NA managed the patient and collected the clinical data. MA and NN reviewed the literature and wrote the original draft. MZ analysed and interpreted the laboratory and imaging findings and prepared the table and figures. ST and SI revised the manuscript critically for important intellectual content. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS APPROVAL

Authors to confirm written informed consent for publication of this case and the accompanying images was obtained from the patient.

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Not applicable

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