2.5 Factors of soil formation

The factors approach to soil genesis provides a systematic way to examine relationships among soils and to explain how and why one kind of soil differs from another. Five soil-forming factors are: parent material, time, climate, organisms, and relief (topography). Each of these factors is considered to be capable of affecting the soil independently. In many instances one or more of the factors may be dependent upon another; for example, organisms may be dependent upon the climate. At other times, the climate may be same but the organisms may differ. For example, at or near a prairie–forest boundary, both the prairie and the forest share the same climate, but the plant and animal populations of the forest and the prairie differ. In such a situation, organisms may have an independent effect.

Jenny (1941) showed how equations for a given soil property, for selected groups of soils, could be developed using the factors approach. The soil property, designated as S for a general equation, was stated to be a function of (dependent on) five factors.

$$S = f(cl, o, r, p, t)$$

where cl = climate, o = organism, r = relief, p = parent material, and t = time.

This equation can be applied to related soils in the following way. If only one of the five factors differs, the remaining factors are considered to be constant. For example, if only time is considered to vary, the equation could be written as:

$$S = f(t)\ cl, o, r, p$$

This equation represents the case when S, a soil property like the organic carbon content of the A horizon, for example, is a function of time or the age of soil, with the other factors remaining constant.

Sequences. Related groups of soils that differ in only one factor have come to be regarded as sequences. Such sequences are referred to by terms that make reference to the factor that is thought to be primarily responsible for soil differences across the sequence. For example:

Lithosequences	Soils differ in parent material.
Chronosequences	Soils differ in soil age.
Rainfall sequences	Soils differ in rainfall.
Temperature sequences	Soils differ in air and/soil temperature.
Biosequences	Soils differ in organisms.
Toposequences	Soils differ only in topography. Commonly these are drainage catenas, or hydrosequences.

Climate and organisms have been considered to be the *active factors*, the driving forces that promote the processes that cause changes in soil or other ecosystem properties during the course of soil genesis. Parent material, topography, and time are called *passive factors*, which may inhibit or resist the general process of soil formation.

2.5.1 Parent material

Parent material refers to the consolidated or unconsolidated initial material from which soil develops. In field examination of soil, the lower stratum, or *C* horizon below the solum, is usually designated as the parent material. In some cases, however, this may not be true; for example, in soil developed in thin, wind-transported material on any rock. The nature of the parent material profoundly affects the properties of young soils, and even of the oldest soils in arid climates.

Parent materials can be divided into consolidated rock materials and unconsolidated materials transported by various agencies—water, ice (glaciers), gravity, and wind. Rock types and their properties have been described in Section 2.2. Parent material may be formed by weathering processes on rocks *in situ* as **saprolite or regolith**, where residual or **colluvial soils** develop. Such materials are common on the slopes of hills and mountains in the northern and western parts of Pakistan. Parent materials may also be transported to other places and redeposited to act as an initial-state soil system.

The transported materials are named according to the transporting agencies and site of deposition. Material deposited by water is **alluvium.** Alluvial material deposited by descending streams, rivers, or even torrents creates the landforms called **alluvial fans,** which coalesce to form **piedmont plains** at the foot of mountain ranges in the highlands of Pakistan. Piedmont plains are characterized by coarse textured and well-drained soil at the apex and fine-textured and poorly-drained soil at the fan base. In arid climates, even accumulated salts occur at the base of the fan. The vast area of the Indus plain consists of river alluvial plains made up of **levees, basins,** and **terraces.** Before it joins the Arabian sea, the Indus river forms a **delta plain** in Sindh province.

Colluvial material is deposited at the foot of steep slopes by gravity. **Lacustrine** deposits consist of the alluvium deposited by rivers in quiet water of lakes. **Glacial drifts** consist of all the materials picked up, mixed, disintegrated, transported, and deposited through the action of glacial ice, or of water resulting primarily from melting of glaciers. This landform is common at high elevations in the northern part of the country. Wind-blown material called **eolian** deposits are either in silt-sized particles (**loess**) or sand particles (**sand dunes**) either stabilized or shifting. Within Pakistan, loess is found in the Pothwar plateau and sand dunes in the deserts of Thal and Thar. The origin or place of removal and time of deposition of these wind-blown deposits are not fully known, however some localized sandy deposits are products of the physical weathering of nearby sandstone, like the sandy *maira* of Swabi and Karak Districts in the NWFP.

Effect of parent material on soil properties. Parent material influences soil formation via its properties, such as mineralogy (chemical composition), texture (grain size), stratification and lithologic discontinuities, lime content or calcareousness, water permeability, and jointing or fracturing. The nature of parent material has a decisive effect on the properties of young soils, and the influence persists even in older soils. The soil properties controlled by parent material are: texture, nature of clay minerals, water-holding capacity, soil permeability, fertility/nutrient status, and toxic elements. In most parts of Pakistan, the active soil-forming factors—climate and organisms—are not very influential in soil formation, so the properties of moist soils remain controlled by the inherited properties of the parent materials and their mode of deposition.

2.5.2 Climate

The climate factor is considered to be the most important factor of soil formation. Climate is the prevailing or average weather conditions at a particular place over a period of years as determined by temperature, precipitation, wind velocity, and other meteorological changes. The climate factor is so complex that no single numerical value can be assigned to a given climate. Moisture and temperature are the two aspects of climate most important in controlling soil properties. The climofunction equation may be split up into two formulae. One expresses soil properties as a function of moisture (m), keeping temperature (T) and other variables constant.

$$S\ (s) = f(m),\ T,\ o,\ r,\ p,\ t$$

The other expresses soil properties as a function of temperature.

$$S\ (s) = f(T),\ m,\ o,\ r,\ p,\ t$$

The climate of Pakistan can generally be described as subtropical continental, ranging from arid/hot or arid/cool to subhumid/humid. Nearly two-thirds of the country's area is hot/very hot and dry with less than 200 mm annual rainfall. A small coastal area has a hot, dry, tropical marine climate. Central Punjab and parts of Peshawar, Kohat, and Bannu regions have semiarid climate with less than 500 mm annual rainfall. Sialkot, Gujrat, and lower Pothwar, Mardan, and Swat have a subhumid climate with less than 1000 mm annual precipitation. A small area of Hazara and Northern Pothwar are cold and humid (annual rainfall more than 1000–1500 mm). Chitral, Gilgit, and the high mountains in other parts of the country have dry, cold, arid climate.

Relationship between soil properties and moisture factors. Moisture is important in soil formation, because water is involved in most of the physical, chemical, and biochemical processes, such as biomass production, mineral weathering and clay formation, translocation of colloids within the soil, and leaching of soluble salts.

Total soil nitrogen and organic matter increase with increasing moisture at a given temperature. This relationship is especially pronounced for grassland soils because there is actual increase in biomass production with increasing precipitation. In arid and semiarid climates most of the water is lost through evapotranspiration, which results in scarcity of vegetation and is responsible for the low nitrogen level of the soils of Pakistan.

In general, soils of arid regions are richer in soluble constituents and plant food than those of humid zones. Little mineral weathering takes place, and the weathering products are not removed from soil through leaching. The presence or absence of a carbonate horizon is an important visible soil characteristic. Well-developed soils in regions of low rainfall have in their profiles a layer of carbonate concretions that contain more $CaCO_3$ and $MgCO_3$ than the horizons above or below. In highly developed well-drained soils of humid regions, the carbonate horizon is usually missing. Under constant temperature, the depth of the $CaCO_3$ accumulation layer increases with increase in effective precipitation. Soils containing a $CaCO_3$ layer are called **pedocals.**

Soils of humid regions have more biomass production and weathering than arid zone soils because of the surplus water available. In general, an increase in precipitation is associated with an increase in weathering and clay formation. Surplus water is effective in the translocation of colloids and removal of soluble weathering products from the solum. Humid region soils, when compared to arid and subhumid soils, tend to have a greater clay content, greater acidity (lower pH), lower base saturation and lower fertility. In extremely humid climates, weathering is so intense that the primary minerals are completely dissolved, releasing iron oxides. Such iron-oxide containing soils have been termed **pedalfers**. Due to high amounts of organic and inorganic colloids in pedalfers, cation exchange capacity and total exchangeable cations (exchangeable bases + exchangeable Al) of the soil increase with precipitation in regions where the temperature remains more or less constant. However, in cold humid regions (e.g. Russia in the latitude of Moscow, western European countries), exchangeable H (Al) (soil acidity) increase is associated with a decrease in exchangeable bases.

In Pakistan there is not enough effective rainfall to show any pronounced effect on soil properties, except that littering, humification, slight decreases in soil pH, and decalcification of the solum have been noted in the cold subhumid/humid mountainous regions (e.g. Murree, Hazara, Swat).

Relationship between soil properties and temperature. Because of intensive weathering, soil depth is much greater in hot humid tropical regions than it is in cold arctic regions, where the depth of the soil is only a few centimeters. Temperature exerts a deciding influence on the balance of the production and decomposition of organic matter. Studies have shown that under belts of uniform moisture conditions and comparable vegetation, the average nitrogen and organic matter content of the soil decreased as the mean annual temperatures rose. This could be due to increased rate of organic matter decomposition with increasing temperature. Van't Hoff's temperature rule: "For every 10°C rise in temperature, the rate of a chemical reaction increases by a factor of two to three", is also applicable to clay formation. The higher the annual temperature, the greater is the clay content of comparable soils. In Pakistan, the mostly arid climate with very hot summer temperatures is responsible for the low organic matter content of the soil. Whatever little plant residue is added is rapidly decomposed, rather burnt, in the hot summer environment.

2.5.3 Organisms

The organisms factor includes both plants and animals, including man. Plants affect soil formation through organic matter accumulation, profile mixing, nutrient cycling, control of the hydrologic cycle, and providing soil structural stability. Plant root exudate and organic matter transformations are sources of energy and nutrients for microorganisms. Some microorganisms, like bacteria and algae, fix atmospheric nitrogen alone or in association with higher plants. Soil animals influence soil formation by consuming or decomposing into organic matter, but their main role is as earth movers. In Jenny's factor approach, organisms are studied as an independent variable of soil formation. However, the biotic factor in pedogenesis is difficult to assess quantitatively because of the dependence of this factor on all the soil-forming factors.

Organisms as dependent variables. Different parent materials/parent rocks support different vegetation types. During soil survey in Merida (Spain), the author observed mostly oak plants on granite and olive plants on granodiorite rocks. In general, as soils get older, changes such as incorporation of organic matter, leaching, mineral transformations, and chemical and physical changes in the rooting medium support different types of vegetation. The broad climatic zones of the world have different vegetation: tropical rain forests, coniferous trees of the temperate zone, short to tall grass of semiarid and subhumid regions, and the thorny bushes of desert climates.

In soils formed on the same parent material, relief controls the natural vegetation. In humid climates, forest is the natural vegetation on well-drained soils on higher positions in the landscape, whereas hydrophytic (water-tolerant) plants (e.g. cattails) are adapted to growing on wet soils in the lower parts of the terrain. Similarly, in arid regions halophytic (salt-tolerant) plants, e.g. *Atriplex*, grow on saline soils found in low-lying portions of the landscape, and less salt-tolerant but more drought-resistant xerophytic plants (e.g. cacti) on the upper dry parts of the slopes.

Organisms themselves can affect the growth of other organisms; for example, biological N_2 is fixed by bacteria in association with host legume plants. The growth of one species may be depressed by the growth of another organism. This situation is called **allelopathy**, the harmful effect of one plant on another through the production of chemical compounds. This can happen between any two types of organisms.

Organisms as independent variables. Soils developed under forest versus prairie vegetation at prairie–forest boundaries have been studied by soil scientists. The forest soils commonly show greater leaching of cations, correspondingly lower pH, and greater clay translocation than do adjacent grassland soils. There is more surface deposition and decomposition of organic matter from trees. On the other hand, the organic matter content of the grassland soils is much higher, especially in the subsurface horizons. This gives the soil a darker colour, and higher moisture and cation exchange capacity than the forest soils have. It leads to the formation of a **mollic epipedon** (surface horizon) in the grassland Mollisols. In forest soils, clay accumulation in the B horizon (argillic horizon) places them in the order of Alfisols.

There are also noticeable differences between soils formed under coniferous and under deciduous trees. Soils under conifers have greater amounts of organic carbon and total nitrogen, lower pH, greater amounts of Na, K and P, and lower amounts of Ca and Mg, than soils under deciduous trees.

Another example of the effect of organisms on soil formation is Basket or Giant podzols under kauri trees (*Agutha australis*) in New Zealand and Tasmania. Litter of a large kauri tree produces a podzol under its canopy, whereas the surrounding soil which is under other types of vegetation has an argillic horizon.

2.5.4 Topography

Topography or relief refers to the configuration of the land surface, and can be described as elevations or inequalities of land surface considered collectively. Some terms employed for describing topography are *level* or *flat*, *undulating*, *rolling*, *hilly*, and *mountainous*. Major topographic features easily recognized are mountains and valleys, escarpments, troughs and ridges, hills, plateaus, and flood plains. All such relief features are present in Pakistan, from the loftiest mountains to the slightly sloping vast plain including the delta of the Indus River.

Relief controls soil formation as an independent variable; however it can also be treated as an interdependent factor. For example, relief influences the distribution of climatic forces and agencies on soil material. The manipulation of climate by relief is readily visible in the differences in vegetation of north and south-facing slopes. The formation of initial parent material is also controlled by relief. In the Indus alluvial plain, levees of higher elevation near river banks have coarser material than the finer-textured initial material of the nearly level basin areas, and the piedmont alluvium near the mountains is coarser and more angular than that of the area further away from the mountain range. Relief itself changes with time: sloping lands are eroded, alluvial plains formed.

Thus topography is commonly considered to be a factor that modifies the effects of the other factors of soil formation. Topography influences profile development through its effects on the quantity of precipitation absorbed and retained in the soil, the amount of water lost as runoff, soil erosion, drainage, and microclimate of the site. Changes in microclimate include temperature differences caused by aspect, the compass direction of the slope, and the combined temperature and rainfall effects which control the type of vegetation on high elevations.

Effect of slope on soil genesis. Slope controls the following soil properties within a specific geographic region: (1) depth of the solum, (2) thickness and organic matter content of the horizon, (3) relative wetness of the profile, (4) colour of the profile, (5) degree of horizon differentiation, (6) soluble salt content, (7) kind and degree of pan development, (8) temperature, and (9) character of the initial material.

The above changes depend upon the steepness and length of the slope. Generally the high areas (hilltops, upper slopes) on convex slopes are relatively dry because of high runoff and low infiltration, have high erosion potential, and are warmer than low areas. Low areas (lower slopes, concave depressions) may be seasonally wet or have permanent high water table; thus they are poorly drained and have a lower temperature. They receive sediments, salts, ions, clays, and carbonates from the upper slopes. Thus the soils on the upper slope are shallow and coarse or even gravelly, lower in pH, soluble salts, and organic matter content, lighter in colour and well-drained; whereas those of lower slope areas are finer in texture, higher in pH, soluble salts, and calcium carbonate, darker in colour, and have impeded drainage.

In the northern hemisphere, soils on south and west-facing slopes receive more direct rays of the sun and are, therefore, warmer and drier than north and east-facing slopes. In the southern hemisphere, the reverse situation holds: north and east-facing slopes are warmer and drier than south and west-facing ones. In cold wet areas, these warmer sites may be more productive because of their more favourable soil moisture and temperature. In arid climates, on the other hand, the south and west-facing slopes have thin soils and less vegetation.

The catena. The term *catena* (Lat. 'chain') describes the suite of contiguous soils extending from hill top to valley bottom. This is a sequence of soils along a slope which are mainly differentiated by topography and drainage. Soil catena indicates a recurring sequence of soils forming on slopes in a generally undulating landscape. The catena is restricted to soils of one climatic zone, although soil microclimate varies.

2.5.5 Time

Most soil-forming processes are time-dependent, so the development of many of the features of soil profiles are also time-dependent. Time itself does not *do* any thing, it acts as a kind of multiplier by which the other factors are manifested in the soil. The relation of soils to time may be discussed with respect to (a) age of the soil, (b) relative stage of development, and (c) rate of formation.

a. Absolute dating of soil horizons and profile. To assess the effect of time on soil formation, it is necessary to measure how long (years) and at what intensity a particular pedogenic reaction has operated on a soil profile. But this is difficult because the value of a soil-forming factor may change with time depending upon climatic changes and other catastrophic events. Time zero is considered to be the time at which the development of a soil begins, i.e. when the parent material starts to be acted upon by biotic or chemical environmental forces. Catastrophic events produce parent materials and provide the opportunity to estimate the age of soil horizons/profiles. Such deposits may be glacial drift, lava flows, mudflows, landslides, accelerated erosional surfaces or deposits, flood deposits, and land creation or land submergence. Scientists have studied the profile development of some of these recent parent materials. However, the majority of soils have an unknown or doubtful time span of development, and might have been formed under multiple sets of soil-forming processes (polygenic) as compared to monogenic soil formed under a single set of processes.

It is well known that world climate, including that of the Indo–Pakistan subcontinent, has changed drastically over geological time; the most recent major changes were associated with the alternating glacial and interglacial periods of the Pleistocene. Major climatic changes were accompanied by the rising and falling of sea level and erosion and deposition, which induced isostatic processes in the earth's crust, all of which produced radical changes in the distribution of parent materials and vegetation, and in the shapes of landforms.

The absolute age of soils can be estimated approximately by tree ring counts, radiometric methods (^{14}C dating and decay of other radioactive elements) or carbonate C in caliche layers. It is estimated that an Inceptisol profile may take 200 years to develop and an Alfisol profile 4000 to 10,000 years, assuming moderate intensity of the factors of soil formation.

Rate of soil formation. Some conditions hasten the rate of soil development; they include warm humid climate with forest vegetation, permeable unconsolidated parent material with low lime content and highly weatherable minerals, and flat topography with good drainage. Factors that tend to retard soil development are cold, dry climate, grass vegetation, consolidated impermeable parent material with poor drainage, and steeply sloping topography.

The rate of soil formation as a whole varies over time. Characteristics of a young soil change more rapidly than those of older soils. The intensity of individual processes also varies over time. For instance, there is rapid accumulation of organic matter in young soil, because the rate of addition is higher than that of decomposition. In mature soil, additions are counterbalanced by losses; and old soil is characterized by declining organic matter. In young soil there is more clay formation because of the presence of primary minerals, while in mature soil there is less. However rates of soil development are extremely variable. Boul et al. (1980) summarized the general picture of rates as follows.

A horizon	1–20 years/cm
A plus B horizon	40–100 years/cm
Complete weathering in the solum	100–750 years/cm

Stages of soil development. A soil profile can attain steady state equilibrium if the rate of weathering of parent material matches the rate of natural erosion. Pedogenic processes, however, generally proceed towards equilibrium at different rates, following a type of 'law of diminishing returns' with respect to time. We speak of **young, mature,** and **old soils** which are weakly, moderately, or strongly developed in morphological characteristics with respect to other soils in the same geographic area, or to soils that are pedologically similar in different areas. Young soils have more properties associated with the parent material, while mature soils have steady state equilibrium with respect to the parent material. In mature soil, different genetic horizons are discernible.