Solar Radiation

Solar radiation is becoming increasingly appreciated because of its influence on living matter and the feasibility of its application for useful purposes. It is a perpetual source of natural energy that, along with other forms of renewable energy, has a great potential for a wide variety of applications because it is abundant and accessible. Solar radiation is rapidly gaining ground as a supplement to the nonrenewable sources of energy, which have a finite supply.

Recent developments in the areas of photochemistry and photobiology have also helped in bringing attention to solar radiation. The significant depletion of the stratospheric ozone layer, which shields the earth from much of the biologically injurious solar ultraviolet radiation (UVR), is apparently due to human activity and has now become a popular topic. Adverse biological effects of UVR on man include, among others, sunburn, conjunctivitis, and skin cancer. In contrast, the vital phenomenon of photosynthesis is an example of the beneficial effects of sunlight in the natural environment. Other beneficial and harmful effects on a variety of living beings, especially microorganisms, are well documented. Solar radiation has, therefore, a prominent ecological role.

Most photobiological investigations have been confined to laboratory work based on the use of monochromatic UVR produced artificially. Because these model studies do not completely reflect the natural situation, the recent trend is to supplement them with experimental work employing sunlight as a natural UV source. This gives results with more realistic, practical values. However, the polychromatic nature of solar radiation, its variable intensity, and the limited knowledge of its distribution at the local level tend to hamper such efforts and complicate the interpretation of the results.

The solar radiation spectrum

The electromagnetic radiation emitted by the sun shows a wide range of wavelengths. It can be divided into two major regions with respect to the capability of ionizing atoms in radiation-absorbing matter: ionizing radiation (X-rays and gamma-rays) and nonionizing radiation (UVR, visible light, and infrared radiation). Fortunately, the highly injurious ionizing radiation does not penetrate the earth's atmosphere.

Solar radiation is commonly divided into various regions or bands on the basis of wavelength. Ultraviolet radiation is that part of the electromagnetic spectrum between 100 and 400 nm. It is, in turn, divided rather arbitrarily from the viewpoint of its biological effects into three major components.

Atmospheric interventions

Solar radiation is partially depleted and attenuated as it traverses the atmospheric layers, preventing a substantial portion of it from reaching the earth's surface. This phenomenon is due to absorption, scattering, and reflection in the upper atmosphere (stratosphere), with its thin layer of ozone, and the lower atmosphere (troposphere), within which cloud formations occur and weather conditions manifest themselves

The stratospheric ozone layer has a strong absorption affinity for solar UVR, depending on wavelength. Absorption, being more effective for the shorter wavelengths, tends to reach its peak at 250 nm and drops rapidly with an increase in wavelength, even beyond 350 nm. Thus, the biological harmful radiations below 280 nm (vacuum UV and UV-C) are completely shielded by the ozone layer; only a fraction of the UV-B and UV-A wavelength bands reach ground level. Depletion of the protective ozone layer beyond the critical level by certain atmospheric pollutants (fluorocarbons and nitrogen oxides) that interact photochemically with ozone will promote the transmission of highly injurious UVR.

The troposphere is an attenuating medium. The solar radiation is reflected and scattered primarily by clouds (moisture and ice particles), particulate matter (dust, smoke, haze, and smog), and various gases. The two major processes involved in tropospheric scattering are determined by the size of the molecules and particles and are known as selective scattering and nonselective scattering. Selective scattering is caused by smoke, fumes, haze, and gas molecules that are the same size, or smaller, than the incident radiation wavelength. Scattering in these cases is inversely proportional to wavelength and is most effective for the shortest wavelengths. The degree of scattering decreases in the following order: UV-B > UV-A > violet > blue > green > yellow > orange > red > infrared. When the atmosphere is clear and relatively transparent, selective scattering is less severe than when it is extensively polluted. Selective scattering of sunlight in the blue region of the spectrum under clear-sky conditions accounts for the blue sky when the degree of scattering is sufficiently high. This is determined by the length of the atmospheric path traversed by sunlight. With the sun overhead at noon, the sky appears white because little scattering occurs at the minimum atmospheric path length. At sunrise and sunset, however, the solar disc appears red because of the increased atmospheric path associated with blue light scattering and relatively little scattering of the red component. Selective scattering may range from 10% in the early morning to 20% in the late afternoon.

Nonselective scattering is caused by dust, fog, and clouds with particle sizes more than 10 times the wavelength of the incident radiation. As scattering in this case is not wavelength-dependent, it is equal for all wavelengths. Because of this, clouds appear white. Clouds also reflect incident solar radiation back into space; this varies with their thickness and albedo (ratio of reflected to incident light). Thin clouds may reflect less than 20% of the incident solar radiation, whereas a thick and dense cloud may reflect over 80%. Absorption of radiation by even thick cloud formations is less than 10%. Whereas gases, water vapour, and particulate matter cause depletion mainly in the short-wave region of the spectrum, atmospheric gases and clouds deplete absorption at specific wavelength intervals called absorption bands. These occur largely in the longer-wave region and are in contrast to the intervening regions characterized by their transmission bands, or atmospheric windows. The gases involved in the absorption phenomenon in the red and infrared regions are ozone and carbon dioxide.

The total solar radiation received at ground level consists of direct and indirect radiation (scattered, diffused, or reflected). The UVR component does not exceed 5% of the total incident radiation at sea level under cloudless atmospheric conditions. The intensity of sunlight at ground level varies with latitude, geographic location, season, cloud coverage, atmospheric pollution, elevation above sea level, and solar altitude. The 23.5° tilt of the earth's axis affects the angle of incidence of solar radiation on the earth's surface and causes seasonal and latitudinal variations in day length. At high altitudes, the intensity of UVR is significantly higher than at sea level. The spectral distribution of solar energy at sea level is roughly 3,44, and 53% in the UV, visible, and infrared regions, respectively. In practice, therefore, these variables need to be considered for the use of solar energy, including its UVR component.

Transmission through different media

Solar energy impinging upon a transparent medium or target is partly reflected and partly absorbed; the remainder is transmitted. The relative values are dependent upon the optical properties of the transparent object and the solar spectrum.

Transmission of the incident solar energy through glass is a function of the type and thickness of the glass, the angle of incidence, and the specific wavelength bands of radiation. Ordinary glass of the soda-lime-silica type (window or plate glass) can transmit more than 90% of the incident radiation in the UV-A and visible regions of the spectrum, provided the Fe_2O_3 content is lower than 0.035%; if it is higher, the transmittance is somewhat decreased. Increased thickness of glass diminishes transmittance. The transmittance is uniform at a high level for angles of incidence ranging from 0 to 40° and drops sharply as the angle approaches 90° (Dietz 1963). Ordinary glass is opaque to radiation in the UV-B and UV-C regions; Pyrex glass (borosilicate type) is opaque to radiation in the UV-B band and attains a maximum transmission level at 340 nm and beyond (Acra et al. 1984). The coefficient of transparency for borosilicate glass, 1.0 cm in thickness, is 0.08 at 310 nm, rises sharply to 0.65 at 330 nm, and attains a peak level of 0.95-0.99 from 360 to 500 nm. The transmission properties of Pyrex are exceeded only by quartz.

Transparent plastic materials such as Lucite and Plexiglas are good transmitters in the UV and visible ranges of the spectrum. Translucent materials such as polyethylene can also transmit the germicidal components of sunlight. Solar energy passing through water is also attenuated by reflection and absorption. The proportion of transmitted sunlight in water depends on water depth; turbidity caused by organic and inorganic particles in suspension; optical properties as modified by the presence in solution of light-absorbing substances such as colouring materials, mineral salts, and humates; and wavelength of the incident radiation. Up to 10% of the solar UV-B intensity at the surface of clear seawater may penetrate to a depth of 15 m, inactivating *Escherichia* *coli* to a depth of 4 m. The exponential attenuation values of UVR (200-400 nm) in distilled water are less than in seawater and range from 10/m at 200 nm to a minimum of 0.05/m at 375 nm. Values rise sharply in the visible and infrared regions of the spectrum, showing that solar UV-A has a greater penetration power in water than UV-B or visible light. The absorption of UVR (210-300 nm) by materials in natural water seems to be related to chemical oxygen demand. At the surface of tertiary sewage lagoons, for example, the solar UV-B intensity drops exponentially to 20% at a depth of 10 cm,3% at 20 cm, 0.6% at 30 cm, and 0.1 % at 40 cm. Most of the UV-B absorbance in wastewater effluents is caused by the dissolved humic substances, whereas the suspended particles absorb and scatter UVR and protect bacteria during UV disinfection.

Textiles used in clothing are not necessarily complete absorbers of natural UVR and may give a false sense of security against sunburn and skin cancer. The average white shirts worn by men may transmit 20% of the solar UVR, whereas lighter weaves favoured by women may allow up to 50% to penetrate to the covered skin. Transmission of UVR through various samples of fabrics ranges from 64% for 100% nylon to 5% for black cotton, the values being reduced by thickness and dyes and increased with the intensity of UVR. The depths of penetration of UVR and visible light into the human skin are as follows: 0.01-0.1 mm for UV-B, 0.1-1.0 mm for UV-A, and 1.0-10.0 mm for the visible spectrum.

Artificial sources of ultraviolet radiation

Artificial sources of UVR are often used for a variety of purposes, ranging from experimenting to suntanning. Gas-discharge arcs, fluorescent lamps, and incandescent sources are some of the common artificial UVR sources, and their potential health hazards are attributable to the significant amounts of biologically effective UVR emitted.

Photobiological research has been confined largely to laboratory work based on the use of UVR produced artificially in preference to solar radiation. The recent trend, however, is toward the use of sunlight as a supplementary source in radiation experiments.

Relevant units

In accordance with the International System of Units, the units for the intensity of solar radiation, or any of its biologically active components, are watts per square metre (W/m^2), or joules per square metre (J/m^2). Wavelength (lambda) is expressed in nanometres (1×10^9). For photobiological research, the term UV fluence (F) is recommended instead of UV dose and its units are watts per hour per square metre (W/h per m^2). Fluence is quantitatively the product of radiation intensity (I) and exposure time (T) ($F = IT$). Another photobiological unit of recent origin is the sun unit (SU), related to the erythemal effect of UV-B radiation.

World distribution of solar radiation

Solar radiation is unevenly distributed throughout the world because of such variables as solar altitude, which is associated with latitude and season, and atmospheric conditions, which are determined by cloud coverage and degree of pollution. The following guidelines are useful for the broad identification of the geographic areas with favourable solar energy conditions in the Northern Hemisphere based on the collection of the direct component of sunlight. Similar conditions apply for the Southern Hemisphere.

The most favourable belt (15-35° N) encompasses many of the developing nations in northern Africa and southern parts of Asia. It has over 3 000 h/year of sunshine and limited cloud coverage. More than 90% of the incident solar radiation comes as direct radiation.

The moderately favourable belt (0-15° N), or equatorial belt, has high atmospheric humidity and cloudiness that tend to increase the proportion of the scattered radiation. The global solar intensity is almost uniform throughout the year as the seasonal variations are only slight. Sunshine is estimated at 2 500 h/year.

In the less favourable belt (35-45° N), the scattering of the solar radiation is significantly increased because of the higher latitudes and lower solar altitude. In addition, cloudiness and atmospheric pollution are important factors that tend to reduce sharply the solar radiation intensity. However, regions beyond 45° N have less favourable conditions for the use of direct solar radiation. This is because almost half of it is in the form of scattered radiation, which is more difficult to collect for use. This limitation, however, does not strictly apply to the potentials for solar UVR applications.

World maps illustrating the isolines of the mean global solar radiation (both direct and diffuse radiations) and solar UVR impinging on a horizontal plane at ground level are available. A set of values for average daily influx of solar UVR as a function of wavelength, latitude, and time of year have also been published. The tabulated data pertain to sea level and clear-sky conditions and are distributed at intervals of latitude from 0 to 65° N and S for selected wavelengths from 285 to 340 nm. The calculated values for the erythemal effect corresponding to 307 and 314 nm have been included for comparison. These data indicate that for all UVR wavelengths from 285 to 340 nm, the solar UVR flux decreases as the latitude increases. Assuming cloudless conditions, the solar UVR intensity at sea level is expected theoretically to be significantly greater at the equator than at the higher latitudes. In addition, at each latitude, the maximum intensity would be reached in summer; the minimum, in winter. A similar pattern will be followed by the erythemal-response wavelengths of 307 and 314 nm. The variation with latitude or season in the calculated influx is much sharper for shorter wavelengths.