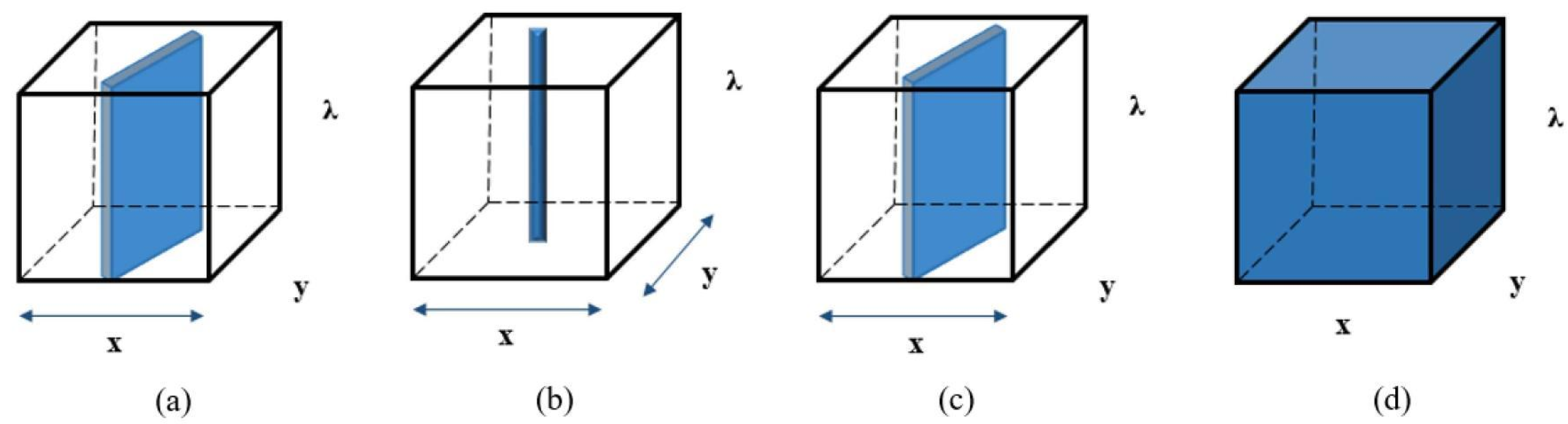

Fig. 2. Some illustrations of image acquisition techniques of hyperspectral image sensors (The arrows represent the scanning directions.) [17]. (a) Push broom. (b) Whisk broom. (c) Filter-based sensor. (d) Snapshot.

to detect genotypes of diseased plants. Therefore, advanced data analytics are required to process the hyperspectral image data effectively.

B. Types and Platforms of Hyperspectral Image Sensors

The selection of sensor type and platform to capture the hyperspectral image strongly affects the applications. This is because sensor types and platforms define how the sensor system's spatial resolution, measurement scale, and throughput will be [15]. In this section, the state-of-the-art sensors and platforms that are used for plant disease detection will be reviewed.

1) Hyperspectral Sensors: Hyperspectral sensors can be mainly divided into nonimaging sensors and imaging sensors. Nonimaging sensors estimate the average reflectance spectrum values of a particular region without taking the spatial information into account. The average reflectance spectrum values depend upon the view angle, focal length, and distance of the sensors to the targeted objects. They are portable in nature, and the measurement techniques are straightforward. The spectral range for nonimaging sensors can range from 300 to 2500 nm with a resolution of 1–3 nm (high). Nonimaging sensors include spectrometers. These are devices that quantify the characteristics of light for a specific segment of the electromagnetic spectrum, resulting in the production of spectral data. Generally, the spectra indicate the intensity of the light relative to its wavelength. For hyperspectral application, comprehensive information about the area of interest (such as leaf) can be obtained by analyzing the spectra. The study of this interaction analysis process is widely referred to as spectroscopy. In other words, spectroscopy helps to comprehend spectral data information from the spectrometers [17], [34]. The spectroscopy technique provides higher spectral resolution but lacks the ability to capture spatial information. Similar to RGB imaging, nonimaging sensors such as spectrometers interact with light. Nevertheless, the RGB cameras can capture only three bands (red, blue, and green) information, whereas spectrometers can capture broad spectrum and detailed information [35]. The popular nonimaging sensors are ASD FieldSpec spectrometers (Analytical Spectral Devices Inc., Longmont, CO, USA), ImSpector (Spectral Imaging Ltd., Oulu, Finland), and SVC (Spectral Vista Corporation, Poughkeepsie, NY, USA) [17]. However, nonimaging hyperspectral sensors are not ideal for plant disease detection. This is because plant disease symptoms often appear at sizes smaller than 1 mm. Therefore, point/area-based measurements might not be suitable for capturing the fine-grained details [15]. The hyperspectral image sensor acquires information across different wavelengths, and it represents both spatial and spectral resolutions. The spectral profile represents how an object reflects light across different wavelengths. This results in the 3-D data/hypercube [17]. There are four main ways to obtain the data/hypercube: 1) push broom; 2) whisk broom; 3) filter-based sensors; and 4) snapshot [15]. Fig. 2 presents the different types of sensors. The hyperspectral imaging sensors capture one dimension of spectral information and two dimensions of spatial data, and this information is highly dependent on the illumination sensor arrays of the cameras. However, the current illumination sensors can only capture the one-dimensional spectral and spatial information. To mitigate this issue, push broom and whisk broom image scanner sensors capture the required spectral and spatial information. A push broom imaging sensor is designed like a scanner to simultaneously capture an entire line of spatial information and hundreds of spectral bands, resulting in a 2-D image [36], [37], [38]. The spatial information is captured across the track, and the spectral information is captured along the direction of the platform motion, allowing a wide range of pixel information. The large spectral information aids the sensor in detecting slight changes in the absorption or reflectance characteristics of the plant's structures to detect stress or diseases. However, push broom imaging requires meticulous calibration to obtain accurate spectral information. Also, the imaging platform needs to be very stable as any tilt can deform the image [36], [39]. On the other hand, the whisk broom sensor is designed to simultaneously capture one-dimensional spatial and full spectral information. A rotating mirror is used to perform the scan perpendicular to the platform motion of the sensor. Compared to push broom imaging, whisk broom imaging allows for obtaining high spectral resolution, which allows for the detection of minute changes in plant tissues or structures [36], [37], [38]. However, the disadvantage of the whisk broom sensors is that it takes longer for data acquisition because they depend on the size of the measured object/area [15], [38].

Filter-based sensors, also known as spectral scanning, operate similarly to the push and whisk broom sensors. However, filter-based sensors can simultaneously measure the spatial image and corresponding spectral bands. The filters, which