Portable NIR spectroscopy: the route to green analytical chemistry

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There is a growing interest for cost-effective and nondestructive analytical techniques in both research and application fields. The growing approach by near-infrared spectroscopy (NIRs) pushes to develop handheld devices devoted to be easily applied for *in situ* determinations. Consequently, portable NIR spectrometers actually result definitively recognized as powerful instruments, able to perform nondestructive, online, or *in situ* analyses, and useful tools characterized by increasingly smaller size, lower cost, higher robustness, easy-to-use by operator, portable and with ergonomic profile. Chemometrics play a fundamental role to obtain useful and meaningful results from NIR spectra. In this review, portable NIRs applications, published in the period 2019−2022, have been selected to indicate starting references. These publications have been chosen among the many examples of the most recent applications to demonstrate the potential of this analytical approach which, not having the need for extraction processes or any other pre-treatment of the sample under examination, can be considered the "true green analytical chemistry" which allows the analysis where the sample to be characterized is located. In the case of industrial processes or plant or animal samples, it is even possible to follow the variation or evolution of fundamental parameters over time. Publications of specific applications in this field continuously appear in the literature, often in unfamiliar journal or in dedicated special issues. This review aims to give starting references, sometimes not easy to be found.

KEYWORDS

NIR, portable NIR, handheld NIR, near infrared spectroscopy, chemometrics

1 Introduction

In the past 20 years, the interest to the potential of near-infrared spectroscopy (NIRs) pushed the development of portable devices devoted to new applications, since several advantages make the technique a powerful analytical tool:

Abbreviations: NIRs, Near Infrared spectroscopy; PCA, Principal Component Analysis; PLSR, Partial least square regression; PLS-DA, Partial Least Squares—Discriminant Analysis; SIMCA, Soft Independent Modelling of Class Analogies.

- The spectroscopic approach is a non-destructive characterization, which allows to have immediate analytical answers that can be correlated to other following characterizations on the same identical sample or its representative portion
- NIR spectroscopy coupled to chemometrics allows targeted or untargeted analysis since the multivariate statistical evaluation of the results allows to develop prediction models
- Results can be reported both as qualitative and quantitative output by means of simple plots that are easily readable even by non-experts in chemometrics or by numerical quantification of the single analyte
- The possibility to perform *in-situ* and online analysis favors industrial applications since spectroscopy can be easily automated and connected to an IoT (Internet of Things) system for direct management of process output
- Increasingly smaller size, lower cost, higher robustness, easy-to-use by operator, portable and with ergonomic profile make NIRs a useful tool for routine characterization.

Chemometrics play a fundamental role to obtain useful and meaningful results from NIR spectra, since prediction models allow to obtain qualitative and quantitative analytical results.

As a consequence, publications of specific applications in this field continuously appear in the literature, often in unfamiliar journal or in dedicated special issues. To have an idea of the scientific interest, inserting "NIR applications" in a search engine like Scopus or Web of Science, more than 13,000 results are listed limiting the search to the last 5 years.

Consequently, to help readers in the search for updated useful starting references, sometimes difficult to locate, in this review have been selected NIRs applications published in the period 2019–2022.

2 Portable NIR spectrometers

Miniaturized and portable NIR spectrometers have enhanced the applications of near infrared technology, nowadays evermore frequently applied in on-site and in-field analyses. Originally used by military, handheld NIR was suddenly discovered by industry for on-site fast quality check. Law enforcement, environmental analyses and food quality control fully recognize the potential of portable spectrometers.

Fast and reliable classification and characterizations for safety or authenticity can be easily performed by trained users, not necessarily scientists (Sorak et al., 2012; Rodionova et al., 2016; Crocombe, 2018; Pomerantsev and Rodionova, 2021). The main goal when the miniaturization is carried out for an analytical instrument is to verify that performance is not affected. Portable NIR actually ensure comparable analytical results to laboratory benchtop devices, in both qualitative and quantitative aspects. Weight is a fundamental parameter for portable instruments: compared to 1 kg of Raman and MIR spectrometers, NIR handheld weight is about 100 g and the close future is the integration into cellular phones (Reinig et al., 2018).

NIR spectroscopy is mainly based on overtone bands and combination vibrations of C-H, O-H, N-H, C=O, and C=C bonds (Workman and Weyer, 2012; Siesler et al., 2016).

Although the signal occurs about ten to one hundred times lower as intensity with respect to medium infrared, the chemometric prediction models make handheld NIR an useful qualitative and quantitative characterization approach in analyses.

Basically, a portable NIR device is very similar to a laboratory benchtop instrument. Miniaturization involves Micro-Electro-Mechanical or Micro-Opto-Electro-Mechanical optical systems. Two main detectors are usually found: array or single detector. Indium gallium arsenide (InGaAs) is the most used material for detectors because of the lower price.

The following main solutions are actually recognized:

(a) Linear-variable filter instruments (array detector).
(b) MEMS-based FT-NIR instruments (opto-electro-mechanical).
(c) Micro-mirror device (DMD™) (wavelength selector).
(d) Fabry-Perot tunable wavelength filter.
(e) NIR grating.

In Table 1 several examples are reported.

Recent publications critically report detector differences (Bec et al., 2021), showing that the signal-to-noise ratio of modern instruments compensates narrower NIR wavelength range.

The sample measurement is highly simplified and makes very easy-to-use the portable NIR spectrometers: by direct contact (but also placing at short distance) it is possible to record characteristic spectra in diffuse reflection.

Figure 1 collects several different portable NIR solutions, commercially available. Simplified principles and parameters are briefly described.

2.1 Instrument improvements

To improve the stability of handheld near infrared spectrometers, a reference correction was proposed by Wang et al. On the basis of the measurement method, it was designed a contrast sampling mechanism to obtain a reference beam from light source. This configuration ensured that reference beam and light source drift in the same trend. An innovative NIR spectrometer for reference correction was consequently developed. According to the experimental results, the stability of the newly designed spectrometer achieved substantial improvement (Wang et al., 2021).

Phosphor-converted light-emitting diodes (pc-LEDs) are employed in handheld spectrosmeters. A high-performance NIR pc-LED was proposed and results demonstrated that the energy transfer can be used for developing new NIR phosphors (Basore et al., 2021). He et al. proposed an innovative pc-LED device, able to scan in a 5-cm-thick chicken breast so to identify characteristic differences in the spectra. The results indicated that biological tissue penetration can be diagnostic (He et al., 2022). To identify affected chicken breasts, de Cavalho et al. proposed handheld NIR spectroscopy. From the experimental results it was shown that myopathies in meat is correlated to the age of slaughter and handheld NIR can be used as a specific tool (de Carvalho et al., 2020).

Soil texture characterization is usually carried on manually, being consequently time-consuming. Vis-NIR handheld spectroscopy is preferred as sensor to predict soil characteristics

TABLE 1 Examples of portable NIR spectrometers available in the market and their monochromator/detector principles.

TrinamiX GmbH, Ludwigshafen, Germany	Linear variable filter instruments
VIAVI Solutions Inc., Santa Rosa, CA, United States	
Texas Instruments, Dallas, TX, United States	Digital micro-mirror device spectrometers
Innospectra Corp., Xinzhu, Taiwan, China	
Spectral Engines, Helsinki, Finland	Fabry Perot tunable filter instrument
Si-Ware Systems, Cairo, Egypt	MEMS FT-NIR spectrometers
Hamamatsu Photonics, Hamamatsu city, Japan	
Southnest Technology, Hefei, Anhui, China	
Insion GmbH, Obersulm,	grating microspectrometers
Germany; OrO Photonics, Xinzhu, Taiwan, China	
Senorics GmbH, Dresden, Germany	NIR scanner with 16 solar cell detectors

(Bene et al., 2020; Benedet et al., 2020; Pham et al., 2021; Andrade et al., 2022; Naimi et al., 2022; Peng et al., 2022; Shrestha et al., 2022; Teixeira et al., 2022; Vohland et al., 2022).

Goi et al. evaluated the possibility of a micro NIR instrument to predict quality parameters in beef. Moisture, fat and protein contents were monitored by a modified PLS analysis. Results proved that the portable instrumentation ensure good levels of prediction (Goi et al., 2022). Grass-fed and grain-fed beef were differentiated by Coombs et al. using NIR spectroscopy with the aim to aid retail and consumer confidence (Coombs et al., 2021).

Yu et al. (2022) prepared innovative OPDs with broad bandwidth, improved responsivity and frequency.

For decades, NIRs demonstrated its potential in industrial process monitoring and quality insurance. Ou et al. (2022). tested a portable NIR in the 850–1700 nm wavelength range. The results from his study demonstrated that the spectrometer, although limited in NIR spectral band detection, can be used in several different sensing applications. Paiva et al. (2022) described the application of diffuse reflectance to liquid and gas samples, enhancing that does not require adaptations. Biodiesel and vegetable oil in diesel blends were determined by comparing benchtop and portable FT-NIR spectrometers.

Bertinetto et al. (2022) investigated the influence of unexpert operator actions in the interpretation of spectra of pig feed.

Miniaturization made possible to develop handheld instruments, so lowering the price of point-of-use analysis. Baumann et al. developed a cheap, handheld DLP-Nano-NIRscan associated to a smartphone for the storage of data. A specific app was developed according to a software design standard. Baumann and coworkers demonstrated the usefulness for plant tissues to determine total nitrogen content (Baumann et al., 2020).

Wang and Liu published a review where they provided a brief summary for the factors that need to be considered in the design of broadband NIR phosphors. Authors expected this review to offer useful guidelines for the development of advanced NIR pc-LEDs (Wang and Liu, 2022).

As a consequence of handheld NIR development, dedicated apps become fundamental tools. Ren and Jia used samples of four drugs as validation objects to test the data classification model, that showed satisficing accuracy and the possibility to overcome internal storage limitations and operating speed (Ren and Jia, 2023).

(Zhou et al., 2022a) used a handheld NIR instrument for powdered sample characterization. The device showed high potentiality in powder analysis and comparative characterization.

Among easy-to-use and cheap analytical instruments, optical multisensor luminescence devices were proposed by Surkova et al. (2022) to determine fat content and adulteration in milk samples.
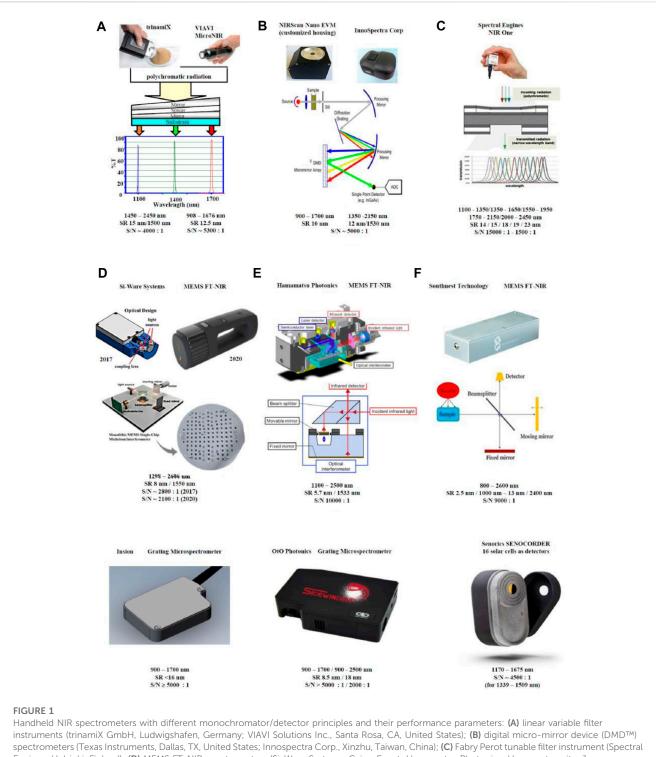
Applications in the Internet of Things (IoT) have been developed. Classic analytical methods, like mass spectrometry and chromatography, are not compatibles with IoT. NIR devices, having no moving parts, are ideal for IoT applications. Applications in industrial and agricultural field have been reported (Wang et al., 2021).

A critical review collected NIR applications, published between January 2019 and July 2020, focused on advantages of this handheld, cheap and robust analytical technique with non-destructive properties. These characteristics insure fast quality control on food products, raw materials, and ingredients (Bwambok et al., 2020). Applications in quality analysis and authentication of nutraceuticals using NIRs was also published in a review by Nagy et al. (Nagy et al., 2022). Reviewed innovation in handheld NIR and summarized and compared their characteristics (Zhu et al., 2022).

3 Applications to food quality characterization and adulterations

Food quality (and consequently food fraud) is often related to profit: the higher is the quality, the higher can be the prize in the market. Frauds or adulterations can result in illicit but important money gain. However, sometimes food fraud can impact the health of customers and consumers. Fraud detection is a challenge to help consumers and to punish food fraudsters.

On the other hand, quality is often a complicated mix of factors not easy to specifically determine or to quantify. NIR spectroscopy creates a specific profile that is the sum of all the specific parameters and can be a fundamental analytical tool. The possibility of managing a "profile" instead of individual analytes allows the NIRs/ chemometrics approach to provide an untargeted result that takes into account all the parameters that characterize the sample

FIGURE 1
Handheld NIR spectrometers with different monochromator/detector principles and their performance parameters: **(A)** linear variable filter instruments (trinamiX GmbH, Ludwigshafen, Germany; VIAVI Solutions Inc., Santa Rosa, CA, United States); **(B)** digital micro-mirror device (DMD™) spectrometers (Texas Instruments, Dallas, TX, United States; Innospectra Corp., Xinzhu, Taiwan, China); **(C)** Fabry Perot tunable filter instrument (Spectral Engines, Helsinki, Finland); **(D)** MEMS FT-NIR spectrometers (Si-Ware Systems, Cairo, Egypt; Hamamatsu Photonics, Hamamatsu city, Japan; Southnest Technology, Hefei, Anhui, China); **(E)** grating microspectrometers (Insion GmbH, Obersulm, Germany; OrO Photonics, Xinzhu, Taiwan, China) **(F)** NIR scanner with 16 solar cell detectors (Senorics GmbH, Dresden, Germany). Reproduced (CC-BY 4.0 license) from (Bec et al., 2021).

under examination and guarantees, in the case of food, to characterize a "profile" of quality as a reference even in case of fraud investigation.

Combining NIR spectroscopy and machine intelligence is a nondestructive tool for powdery food evaluation. Zhou et al. presented a handheld device ("NIR-spoon") for simultaneous evaluation of multi-mixture powdery food. Each mixed powdered sample was analyzed by a "NIR-Spoon" and software was consequently dedicated to the "NIR-Spoon" that resulted in a good accuracy with the possibility of a mobile app (Zhou et al., 2022b). An OPLS-DA model, based on the data from the handheld NIR, showed 84.85% and 86.96% correct classification (Srinuttrakul et al., 2021).

The determination of green pea and peanut adulterations in pistachio by handheld FT-MIR and FT-NIR spectroscopy was proposed by Aykas and Menevseoglu. Pistachio adulteration derives from its high value. A fast FT-NIR methodology to check adulteration was proposed and provided advantages over FT-MIR, being more precise (Aykas and Menevseoglu, 2021). Cashew nut adulteration with Brazilian nut, pecan nut, macadamia nut and peanut was proposed, based on the development of a one-class SIMCA model (Rovira et al., 2023). Zhu et al. evaluated quality traits of oats to support breeding selection (Zhu et al., 2022).

Prediction of meat quality in fresh cut was reported by (An et al., 2022), while after treatment in the abattoir was reported by (Savoia et al., 2020; Savoia et al., 2021). Li et al. proposed a rapid and nondestructive simultaneous characterization of different types of sheep meat cut (Li et al., 2021).

Extra virgin olive oil is among the most known quality made in Italy product. Violino et al. (2022) evaluated the performance of a handheld VIS–NIR system to determine 203 oil samples quality. Ciaccheri et al. reported a bluetooth-connected pocket NIR spectrometer for the analysis of olive oils of different qualities (Ciaccheri et al., 2022) and a similar study was published by Santos and coworkers (Borghi et al., 2020; Santos et al., 2020; Santos et al., 2022).

Escuredo et al. (2021a). proposed a simple portable spectroscopic approach to predict the properties in honeys by multivariate data processing.

Maraphum et al. used a portable NIR spectrometer to determine starch and dry matter amount in fresh cassava tubers. Results suggested that the method can be useful when monitoring the quality of cassava tubers "in field" by breeders, with save of time and costs (Maraphum et al., 2020; Maraphum et al., 2022). In coriander oil can be found about the 70% of petroselinic acid, with anti-inflammatory and anti-aging properties. The authenticity of coriander oil and modifications by means of commercial oils was tested by handheld NIR and PLS regression models (Kaufmann et al., 2022). Edible oils are usually adulterated with sesame oil to save production costs. Portable FT-NIR, FT-MIR, and Raman spectrometers were proposed as rapid, simple, and non-invasive method to detect adulteration (Menevseoglu, 2021).

Truffles are well known and very expensive edible mushroom. Black truffles can be however found at lower prices. It is not easy to distinguish truffles without experience and often frauds occur. Kappacher et al. analyzed truffle samples of different species by 4 NIR devices: of these, 3 were miniaturized devices (Risoluti et al., 2020a). The resulting published paper compared the predicting performances of portable vs. benchtop NIR instruments, suggesting a fast, non-destructive and cheap tool (Kappacher et al., 2022).

The raspberry characterization is a procedure laborious and expensive, due to several chemical tests to use. By a NIRs approach, the prediction of raspberry quality was proposed by Gales and coworkers. Anthocyanins and solid soluble concentrations in whole fresh raspberries were easily predicted (Gales et al., 2021).

Sripaurya et al. (2021) designed and implemented a 6-digital-channel portable NIR instrument to determine the quality and the maturity of Gros Michel bananas. Portable NIR to in-field determine "Valencia" orange fruit maturity and avocado was reported by

Ncama and coworkers (Ncama et al., 2020a; Ncama et al., 2020b). The evaluation of portable spectrometers performance to characterize table grape and peach quality attributes non-invasively, was proposed by (Donis-González et al., 2020), by (Rouxinol et al., 2022), by (Zhang et al., 2021), by (Ferrara et al., 2022) and by (Beltrame et al., 2021).

Almonds, easy to adulterate to have higher profits because of the lower production costs, were characterized by a developed method for identification of almond flour adulteration by comparing three different portable NIR instruments and SIMCA as classification method (Netto et al., 2023). Bitter almonds contamination in sweet almonds was determined by by the potential of portable NIR (Torres et al., 2021). Wang et al. realized a handheld Vis/NIR prototype to discriminate different origin apples (Wang et al., 2022).

Manuelian et al. evaluated cheese total nitrogen, soluble nitrogen, ripening index, major minerals, and fatty acids by a pocket-size NIR spectrometer. When comparing the accuracy with a benchtop instrument, however, no substantial difference in accuracy resulted. The NIR miniaturization can consequently be an opportunity in dairy industry (Manuelian et al., 2022). Bittante et al. published an invited review with focus on VIS and NIR spectroscopies to predict the cheese chemical composition (Bittante et al., 2022).

Omega-3 supplements are sold at elevated prices and their quality has to be assessed. Hespanhol et al. evaluated the performance of a cheap NIR assisted by a chemometric model to determine the concentration of omega-3 in supplements. This simple, fast and inexpensive approach determined the quality of the supplements and to identify frauds or non-conformities of the market (Hespanhol et al., 2020).

Durum wheat semolina is the raw material for pasta production and, when cooking, are fundamental the protein content to obtain the gluten strength. Cecchini et al. compared two technologies (both non-destructive and rapid), i.e. a low-cost sensor and a handheld NIR spectrometer, to determine semolina quality. Experimental evidence enhanced the possibilities of a small and low cost sensor, easy to use in contact with the sample more than by a laboratory instruments (Cecchini et al., 2021).

Intrinsic and extrinsic properties of rice were studied to give the consumer a rice quality identification. Spectra were collected by a handheld NIR to develop a predictive model (Rizwana and Hazarika, 2020). Jiang and coworkers reported a fatty acid surveillance during the storage of the rice by a handheld near infrared system (Jiang et al., 2020).

Insects are well known as possible human food. Riu and coworkers studied the possibility to classify insect powder by handheld NIR spectrometer. Experimental evidences confirmed this instrumental approach to be a trusted tool of analysis, able to predict macronutrients (Riu et al., 2022).

The moisture content deeply influences the dehydration process to prevent microbial growth and to preserve nutrients and quality of fruits and vegetables. The results of a study proposed by Malvandi showed how a handheld NIR is able to monitor the moisture content (Malvandi et al., 2022a). Pesticide residues determination was presented by Ngo et al. on leafy vegetables using a handheld VIS/NIR instrument. Vegetable samples, like lettuce, oriental mustard, and bok choy, were analyzed. Results showed that

pesticide residues on leafy vegetables can be easily detected (Ngo et al., 2022). Recently, handheld and smartphone-based NIR devices have been widely used in agri-food industries as food-scanners, based on their predictive potential and compared with destructive approaches (Goisser et al., 2021). Integrated soluble solid and nitrate content assessment of spinach plants using portable NIRS sensors along the supply chain was also reported by (Torres et al., 2020)

Mishra and Woltering used an innovative approach that was tested to predict moisture and total soluble solids in pear and kiwi fruit (Mishra et al., 2021; Mishra and Woltering, 2021).

Anyidoho et al. (2022). used NIR/Chemometrics for rapid determination of fermentation duration, fermentation index and moisture content of cocoa beans.

The watermelons maturity was determined by two handheld new generation NIR spectrometers were compared in determining soluble solid content, a parameter that proves full watermelon maturity. The results obtained by different pre-processing methods showed the possibility to predict watermelon maturity (Vega-Castellote et al., 2022). Qi et al. discriminated the different varieties of red Jujube (Risoluti et al., 2019a; Qi et al., 2022).

Lycopene ia a red colored carotenoid in tomatoes that shows health benefits in scavenging free radicals. Instead of traditional in laboratory extraction process followed by HPLC analysis, Goisser et al. compared Vis/NIR spectra obtained by three portable Vis/NIR instruments defined food-scanners (Goisser et al., 2020a; Goisser et al., 2020b). The commercialization of fresh tomatoes is based on the soluble solid content as quality parameter. A handheld Vis-NIR spectrometer in interactance geometry discriminated low from high values soluble contents (Brito et al., 2021). Food waste has to be reduced as much as possible. Emsley et al. assessed the NIR potentiality to prove tomato stability during storage. Resulting informations indicated the possibility to predict tomatoes time-after-harvest (Emsley et al., 2022). Arruda de Brito et al. also proposed the possibility to determine important parameters (color, dry matter, etc) by NIR spectroscopy (Arruda de Brito et al., 2022). Handheld NIR for in-field fresh tomato quality control analysis was reported by (Borba et al., 2021) and by (de Oliveira Aguiar et al., 2022).

Gatti and coworkers investigated by handheld NIR milk chocolate, white chocolate and other different percent cocoa chocolates subjected to high temperatures. Good sensibility, specificity, and accuracy values were determined to establish thermal treatments (Gatti et al., 2021).

To assess fishery products authenticity it is fundamental an instrumentation able to give rapid, eco-friendly, cost-effective and easy answer. Varrà et al. verified the possibility to determine the geographic origin of two octopus species by a handeld-ultra-compact NIR. The results suggested the possibility to in-site or on-line monitoring fishery products (Moon et al., 2020; Varrà et al., 2022). Non-destructive characterization of salmon and tuna freshness was proposed by (Cui and Cui, 2021). Fish identification is not easy neither for consumers nor for inspectors, especially when prepared as fillets. To develop fast detectors, Cavallini et al. distinguished very similar fish species by comparing handheld SCiO (Consumer Physics), MicroNIR (VIAVI) with benchtop MPA (Bruker). (Risoluti et al., 2015; Pennisi et al., 2021; Cavallini et al., 2022). Handheld NIR spectroscopy was proposed as discrimination tool between wild and farmed sea bass by (Esposito et al., 2022). Yakes et al. (2021)

reported the analysis of two fish species and compared the performance of handheld NIR devices. Currò et al. (2021) proposed handheld NIR instrument as a fast and green method to check the origin of cuttlefish. Yu et al. (2020) assessed by rapid and nondestructive application of handeld NIRs the freshness of tilapia fillets.

By means of a calibrated image analysis, (Tugnolo et al., 2021) and by (Grassi et al., 2021) evaluated the maturation of olives. Comparative analysis was reported by optical fiber probe/benchtop NIR device. Considering the vis/NIR model good performance, an algorithm was applied.

Butteroil has sensory characteristics, economic importance, and because of the high value it can be replaed by other cheaper fats. The potential of handheld NIR spectroscopy to detect butteroil adulterations was suggested to help producers and inspectors in the supply chain (da Silva Medeiros et al., 2023).

Pepper spice adulteration is a growing problem. Evidences from analyses by a handheld NIR demonstrated that adulteration of white pepper can be easily identified (Chen et al., 2022). Oliveira and coworkers proposed PLS-DA and PLSR models (based on handheld NIR spectra) as adulteration identifiers of Paprika powder (Oliveira et al., 2020).

Ouyang and coworkers proved the possibility to predict by handheld NIR spectroscopy the total nitrogen content in pork meat (Kucha and Ngadi, 2020) or frozen pork meat (Ouyang et al., 2020). Portable NIR and machine learning was proposed by (van Kollenburg et al., 2020) and by Parastar and coworkers (Parastar et al., 2020) to determine the authenticity of chicken fillet. Beef, pork, and chicken quantification in ground meat was reported by (Silva et al., 2020).

Milk quality can be evaluated by the content of fats, proteins, lactose and total solids. Adulteration of goat milk by cow milk was proposed by (dos Santos et al., 2021) and by Muniz and Cuevas-Valdés (Muñiz et al., 2020). To authenticate milk geographical origin, Zhang et al. proposed the use of portable NIR spectroscopy to correctly and rapidly detect the adulteration (Zhang T. et al., 2022). To rapidly and conveniently detect the compositions of milk, a handheld detector was developed by Yang et al. 120 raw samples helped to set up the PLSR model to predict the main composition (Yang et al., 2020). A review on the recent advances in NIR portable spectrometers and the applications to milk, cheese and dairy powders was published by (Pu et al., 2021). That is widely supplied in the market has three main active ingredients, including. Ashie and coworkers determined, by portable NIR spectroscopy, active ingredients like silybin, silychristin and silydianin, and isosilybin in milk thistle extract because of their valuable functions for the human body. Results showed that SNV and first derivative discriminate silybin and isosilybin (Ashie et al., 2021). Water adulteration in raw milk of bovine was detected by Ehsani et al. (Ehsani et al., 2022) and by (Riu et al., 2020) who applied classification and regression techniques to spectra from handheld near infrared spectroscopy for facile and rapid detection. Risoluti et al. (Scala et al., 2018) and (Galvan et al., 2022) demonstrated that low-cost handheld NIRs and EDXRF spectrometry coupled to chemometrics can differentiate authentic cow and goat milks from whey mixed ones.

Human milk banks recently expanded because of the newborns growing need. However, human milk composition analyses are far

from routine possibility. Jorge dos Santos and coworkers developed a comparative spectroscopic approach by a portable MicroNIR to compare composition of human milk (Jorge dos Santos et al., 2021) and its conservation (dos Santos et al., 2022). Melendreras et al. (2022) characterized breast milk composition along the lactation period. The results proved the richness of near infrared spectra, and specific bands provided excellent quantitative models.

Lanza et al. (2021) compared benchtop with handheld NIR characterization to discriminate refrigeration periods of chicken breast. PLS-DA indicated correct shelf-life prediction.

A fast online estimation of quail eggs freshness was proposed by (Brasil et al., 2022) and by (Cruz-Tirado et al., 2021).

Alcohol content is essential for the quality control of beers. To this aim, a new rapid and direct multivariate method was proposed and validated using a portable NIR spectrometer and PLS regression, supported by a parallel GC-FID method (da Costa Fulgêncio et al., 2022). Foam parameters are related to beer quality and depend on the protein amount. Viejo et al. used machine learning to predict 54 proteins. Fifteen parameters with handheld NIR assessed significant correlations to physical parameters (Viejo et al., 2020).

Escuredo et al. (2021b) determined quality parameters for potatoes by a MicroNIR device, such as dry matter and reducing sugars. PCA and modified PLS models demonstrated to be useful for potato processors. $NaSO_3$ acts as browning inhibitor when storing potato slices. However, sulfur dioxide residues can be formed, very dangerous to health. NIR hyperspectral imaging was demonstrated to be able to classify SO_2 residues (Bai et al., 2020).

Technicians and producers of dairy farm forage need rapid and reliable equipment to control the quality, better if in unexpensive and easy-to-use way. Rego and coworkers presented a portable-NIR-based procedure to analyze the nutritional values of dairy farm forage. By means of Internet of Things (IoT) tools, spectra can be sent to cloud to be processed and accessible to any device. A chemometric model was developed and validated (Rego et al., 2020).

Productivity and wellness of animals can be improved by precision nutritional composition forage. Near infrared spectroscopy demonstrated to be a very useful tool to determine the nutritional content of forage (Rukundo et al., 2021a; Rukundo et al., 2021b).

Beć et al. (2022) published a thematic review to collect the applications of food-analysis miniaturized NIRs, enhancing challenges and perspectives.

4 Applications to drugs

The surveillance of medicines is of fundamental importance to guarantee and protect the consumer, especially when the medicines are life-saving or have a strong impact on the patient's therapy. Consequently, the surveillance of medicine devices is fundamental. NIR spectroscopy plays an extremely interesting role, given the possibility of checking the product without necessarily taking sample aliquots. The ability to carry out analyses, for example, directly inside the packaging blister is now known. Several authors have published interesting scientific applications to drug surveillance and characterization.

Caillet et al. tested six devices' utility and usability in detecting substandard and falsified medicines: four handheld spectrometers

(two near infrared and two Raman), one portable MIR spectrometer and a single-use paper analytical device (Caillet et al., 2021; Greco et al., 2023a; Greco et al., 2023b). Laboratory evaluation of twelve portable devices for medicine quality screening was proposed by Zambrzycki and coworkers, including portable instruments (Zambrzycki et al., 2021).

Illicit-drug seizures are a growing problem since the forensic drug identification is not easy to perform, especially in case of new psychoactive substances. Kranenburg and coworkers (Kranenburg et al., 2022a; Kranenburg et al., 2022b; Kranenburg et al., 2022c) and Awotunde and coworkers (Awotunde et al., 2022) introduced a handheld NIR with a 1,300–2,600 nm range. A specific chemometric model was developed for forensic samples. Authors report that it only requires few reference spectra for training the model, thus eliminating the need of extensive training sets including mixtures. The early detection of emerging street drugs by near infrared spectroscopy and chemometrics was extensively studied by Risoluti and coworkers (Risoluti et al., 2016; Materazzi et al., 2017a; Risoluti et al., 2019b; Risoluti et al., 2019d; Risoluti et al., 2020f).

An innovative screening platform was realized and validated for the detection of cannabinoids on-site in hemp seed oil, aimed to food safety control in market products. This completely automated tool is based on a miniaturized NIR in wireless mode that allows rapid and accurate sample processing and the early detection of residual cannabinoids in oils, including CBD, Δ9-THC and the Δ9-THCA (Risoluti et al., 2019c; Risoluti et al., 2019d; Risoluti et al., 2020b; Risoluti et al., 2020c; Risoluti et al., 2020d) and amphetamine (Risoluti et al., 2020e).

A discrimination of falsified Amoxicillin capsules using heterogeneous NIR spectroscopic devices for training and testing of a support vector machine (Hattori et al., 2021). A handheld NIR spectrometer was employed to quantify heroin was described by Hattori et al. samples by PLS regression and applied to determin heroin casework samples in the concentration range 4.49%–88.05% (w/w). The approach showed good results as repeatability and precision and the results demonstrated an acceptable model performance as on-site heroin detection instrument (Chen et al., 2021).

When considering a pharmaceutical manufacturing process, the ensurance of quality is needed either in the final product or in intermediates. A Raman probe and a portable NIR were applied at the blending process exit. Both the predictive models were tested for accuracy, precision, operating range, measurement frequency, placement, reliability, robustness (Panikar et al., 2021). Hattori et al. (2022). improved algorithms to screen falsified or substandard amoxicillin capsules. FT-NIR and portable wavelength dispersive NIR spectrometers validated the proposed approach. Zhong et al. (2022) proposed the handhelded NIR spectroscopy for the evaluation of coating uniformity of digestion-aid tablets.

A specific review was proposed by Usman et al. to resume the different applications of portable or miniaturized medium-IR, near-IR and Raman instruments for efficient control of quality in pharmaceutical products. These portable spectrometers demonstrated to be a powerful tool to identify of counterfeits, adulterated, fraudulent, falsified, and substandard pharmaceutical capsules or drops (Usman et al., 2020).

The possibility to evaluate Low-Cost Optical Spectrometers to detect falsified medicines is a growing need. Medicines are often counterfeit and is fundamental to warrant rapid, sensible and nondestructive methodologies for the characterization of products. Handheld NIR was proposed by (Wang et al., 2020) and by Assi et al. to authenticate branded or generic antibiotics. The resulting NIR spectra showed characteristic spectra for the main component(s) (Assi et al., 2021). Three-dimensional printing is a revolutionary technology in pharmaceuticals, enabling the personalisation of flexible-dose drug products and 3D printed polypills (polyprintlets). Polyprintlets were non-destructively characterized using a handheld NIR and calibration models were proposed by (Trenfield et al., 2020).

There is a market of seized controlled substances in combination with drug-of-abuse in which new substances psychoactive have to be identified by rapid and reliable presumptive drug testing, better if on-site. Spectroscopic techniques show several advantages because spectra are specific and non-invasive analyses are possible. NIRs is a promising technique for forensic drug detection directly "on-scene". Several portable spectrometers were sold in the past years. Kranenburg et al. realized a dataset of spectra with 430 samples, including illicit-drugs, NPS, adulterants, bulking-agents and excipients. By this dataset, illicit-drugs spectra were usable by institutes that not easily get access to controlled substances and can be of help in developing chemometric models to detect illicit-drugs (Kranenburg et al., 2022d; Kranenburg et al., 2022e).

Since 2019, COVID-19 has exploded as a global pandemy. The possibility to have false vaccines gave illusion of security, highering the exposure to the virus, and increasing the risk of infection. Assi et al. proposed a non-destructive handheld NIR approach for verification of COVID-19 vaccines. Bands corresponding to the mRNA active ingredient were detected by NIR. PCA allowed the validation of COVID-19 vaccines (Assi et al., 2022). As a parallel security procedure, alcohol-based hand sanitizers were recommended as a strategy to minimize contamination. By handheld NIR with PLS-DA, models were realized to check for conformity of commercial hand sanitizing products, while PCA was proposed to test a exploratory study. Results indicated that NIR spectroscopy with chemometrics are a promising tool to discriminate hand sanitizers and able to detect the right ethanol concentrations (Pasquini et al., 2020; Silva et al., 2021).

Aerial parts of Cannabis spp. can be easily purchased; however, in the cannabis not only is present cannabidiol, but Δ9-tetrahydrocannabinol can also be detected and its psychotropic effects are well known and its presence in high concentration is illegal in almost all the European countries. Officers need to test the Δ9-tetrahydrocannabinol concentration in questioned samples. In addition, a portable equipment is of sure interest for farmers to control the THC content in time. Duchateau et al. analyzed hemp flowers and compared results from benchtop or portable NIR devices. A GC-FID analysis determined in parallel the related THC concentration. The proposed models clearly discriminated legal and illegal cannabis samples on the base of European and Swiss laws (Duchateau et al., 2020).

Women use medroxyprogesterone when hormonal therapy is needed. In case of falsification, health risk could result for consumers. A handheld spectrometer with open-sourced software was tested by Eady and coworkers to evaluate vials of Medroxyprogesterone acetate injectable suspensions from different suppliers and results were validated (Ead et al., 2021).

Anti-leishmanial pentamidine bioconjugates based on PLGA-PEG and hyaluronic acid were described by Scala et al. (Ca et al., 2018).

5 Applications in medical diagnostic

NIR spectroscopy demonstrated to be a very helpful tool in medical diagnostic. The non-invasive spectral characterizations, with the fundamental help of chemiometric evaluation and machine learning, have been scientifically proved to be a fast and sensitive preliminary approach for a preliminary health check. Several publications can be found in recent literature.

Traumatic brain injury can lead to hematomas or edemas inside the cerebral tissue. To this end, low-cost, portable and easy-to-handle devices can be fundamental in continuous monitoring. NIR based techniques have been proposed as good solution. Vera et al. used time resolved Monte Carlo simulations in a handheld NIR study. Results showed that mean partial pathlengths, photon measurement density functions and time dependent contrasts are influenced by lesions, proving to be robust means for diagnose or monitoring (Vera et al., 2022). For the strict control of solid oral preparations, Zhang et al. (2022) studied how to determine the content of active pharmaceutical ingredient by a portable NIR sensor in the production line.

Hafiz and coworkers proposed a new hand-held camera for retinal imaging including white or NIR-LED adjacent to each other, able to illuminate by NIR without additional beam-splitters or filters. The camera was adapted to be interfaced to Android-based smartphones to determine ocular safety analysis (Hafiz et al., 2022).

Bhattacharya et al. presented the development of a NIR-portable instrument to detect acute ischemia stroke by means of albumin in human blood serum. The test on human blood samples showed good linearity to determine the concentration of albumin in human blood (Bhattacharya et al., 2022). Similar studies related to the detection of hematologic pathologies were reported by Gullifa et al. (Risoluti et al., 2019e; Risoluti et al., 2020f; Risoluti et al., 2020g; Gullifa and Risoluti, 2021). The dynamic control of lymphatic and vascular systems was published by (Wang et al., 2022).

An unusual study was proposed by Ni and coworkers, who evaluated handheld-NIR possibility to in vivo analyze healthy tissues and to correlate the results with age. Partial Least Square regression showed that vibrational spectroscopy non-destructive techniques can be used as useful tools to relate interactions between physiology and nutrition (Ni et al., 2022a). Ni et al. also evaluated the ability of an handheld NIR to relate spectral informations to food and energy intake, satiation, and satiety data. Results showed the potentiality of in-vivo NIR spectroscopy to differentiate tissues (Ni et al., 2022b). Clemson et al. (2022) proposed a portable and non-contact system for skin surveillance.

Diabetes is a life-threatening disease and needs constant monitoring of blood glucose levels. Yu and coworkers proposed a mobile application for handheld NIR useful to non-professional users. The experimental results showed that the portable and light NIR spectrometer can be easily used (Yu et al., 2021a). A NIR-LEDs-Based detection system was also proposed by Badriah et al. to measure blood sugar levels on diabetic care (Badriah et al., 2022).

Belay et al. (2020) presented a three-segment grating spectrometer, aimed to help in cancer diagnosis. The results experimentally proved

that this solution significantly improves the spectrometer signal. With the same view, Bonapace et al. (2021) described how to determine methylglyoxal adducts content by portable handheld NIR. MicroNIR/ chemometrics determination of hydroxyurea occupational exposure was also proposed as a new tool in work-surveillance and prevencion (Risoluti and Materazzi, 2018).

In a review published by Huang et al., a smartphone-based NIR fluorescent imaging technology was proposed. Smartphones can improve diagnoses being a tool for real-time diagnosis, even in remote regions (Huang et al., 2021). Hasan et al. proposed a state of the art review, collecting the predictive and non-invasive techniques of hemoglobin level (Hasan et al., 2021).

6 Applications to agriculture

Portable systems can be of fundamental usefulness for in-site material characterization and quality analysis in agricultural. Miniaturized NIRs were proposed in material-sensing applications. To validate the performance, several classification algorithms were compared (Behera et al., 2020).

B1 and B2 fumonisin rapid detection in corn was described by Shen and coworkers by smartphone-based handheld NIRs/ chemometrics (Shen et al., 2022).

ESI(±)FT-ICR MS and portable microNIR were proposed as a new analytical tool to characterize Robusta coffees. A published study confirmed that both can be efficiently applied to coffee quality control, with many advantages such as speed and analytical reliability (Correia et al., 2020). Baqueta and coworkers directly evaluated cupping profiles in coffee blends via portable NIR and PLS-DA model. Results were presented as industrially interesting and the method could help coffee professionals in cup evaluation (Baqueta et al., 2021). A one-class classification method was proposed to control agroforestry-grown coffees by (Manuel et al., 2022).

Forage analysis by NIR spectroscopy had many advancements since 1970. Due to instrumentation, computers and chemometric algorithms improvements, it is actually the most used approach for the routine analysis by forage producers, plant breeders, animal nutritionists, cattle farmers, and feed companies. Berzaghi et al. (2021) reported a comparison among three different portable instruments and a benchtop lab instrumentation, using many forage samples.

Phenotyping information is fundamental for sugar industry. Gaci and coworkers proposed a micro-, low-cost, portable narrow VIS-NIR instrument to get a PLS predictive model (Gaci et al., 2022). Henrique da Silva Melo and coworkers evaluated portable spectroscopy for the quantification of brix and pol in a sugar production plant (Henrique da Silva Melo et al., 2022).

Edible oils, modified lipids, industrial oils, and biofuels can be produced by Brassica. Analytical methods based on Portable NIRs and NIR-Hyperspectral Imaging were applied to characterize seeds species (da Silva Medeiros et al., 2022). Jiang et al. (2022) and (Bilal et al., 2020) proposed a fast way to determine peanuts acidity index. Yu and coworkers classified the high oleic acid peanuts by comparing portable and benchtop NIRs. The accuracy of distinction was 100% with both the instruments (Yu et al., 2020). Jiang et al. (2021) and (Giussani et al., 2021) used a handheld NIR device to analyze the acid values during the storage of edible oils. Grossi et al. (2020) proposed a procedure to determine solid fat by single-wavelength NIRs.

Yao et al. developed a rapid NIR authentication procedure for exhaust oils used in frying potato chips. A miniaturized NIR sensor showed how handheld vibrational spectrometers can provide a rapid *in-situ* identification of oil type and could be a surveillance tool of the products (Yao et al., 2021).

Data from three different NIRs were analyzed to compare coriander seeds. Three instruments were compared in their prediction ability. 200 authentic coriander seeds spectra were compared with 90 adulterated samples (McVey et al., 2021). Often consumers of seedlings or fruits have troubles to recognize if that product really is what is indicated by the merchant. Consequently, it becomes particularly crucial to evaluate the marketing process. Vinhandelli et al. used PC-LDA or PLS-DA algorithms to test the ability of NIR spectroscopy to discriminate cultivars (Vinhandelli et al., 2023). Nitrogen assessment in strawberries by handheld FT-NIR was also proposed by Wu and coworkers (Wu et al., 2020).

A cost-effective and fast analysis of nutrient content in cotton leaves by handheld NIR spectroscopy was reported by (Prananto et al., 2021).

Quantitative assay of Aflatoxin B1 in maize was proposed by Deng et al. Their NIR system was realized and employed to characterize maize samples with different mildew degrees (Deng et al., 2022). High-quality production of tobacco leaves needs identification of deep green infection. Janqiang et al. proposed an identification methodology for deep green tobacco infections using a portable NIR (Jianqiang et al., 2020).

Detecting of apple valsa cancer is useful to prevent diseases and to check apples yield and quality. Zhao et al. proposed portable NIRs and Raman scattering spectrometers in reflection mode using machine learning to predict infection degrees (Zhao et al., 2021). Qiao and coworkers proposed apple sugar content determination by handheld tool connected to a cellular phone (Qiao et al., 2020). Apple hardness can be determined by non-destructive, as proposed by (Malvandi et al., 2022b) and by (Ma et al., 2021a).

The citrus industry is always searching for instrumental methods able to determine in real time and *in situ* the modifications of fruit development or storage, with a special focus on vitamin C. A NIR-based model was proposed to vuate the ripeness (Santos et al., 2021). Jahani et al. (2020) proposed a miniaturized handheld NIR as a preliminary test of adulterasin in lime juices coupled with classification methodologies.

The current practice by potato growers for tissue testing is based on petiole chemical analysis rather than leaf analysis. AbuKmeil and Al-Mallahi estimated nutrients in potato intact fresh leaves by a portable Vis-NIR spectrophotometer and the parallel chemical analyses were done on petioles following the official methods of the AOAC. The Lasso models showed a fair distribution of nitrogen, phosphorus, potassium, calcium, magnesium, and zinc with coefficient of determination values above 0.5 and acceptable to excellent RPD values (abuKmeil and Al-Mallahi, 2022).

Wang and coworkers (Wang et al., 2020; Wang et al., 2020; Sun et al., 2020; Wang et al., 2021; Jin et al., 2021; Ren et al., 2022) developed a handheld tool to check the freshness of tea.

The contamination of bee pollen by pyrrolizidine alkaloids is actually determined by LC-MS. De Jesus Inacio and coworkers suggested the use of fast NIR spectroscopy as alternative and accurate approach (De Jesus Inacio et al., 2020).

In the livestock and poultry breeding industry, the slurry is a mixture of urine, feces, flushing water, and disinfectant. The composition varies

greatly when returning to the field, due to several different influencing interferences. Liang et al. developed a NIR method to *in-situ* determine the slurry characteristics (Liang et al., 2022).

7 Applications to forensics

The use of portable NIR devices in forensic analysis has recently undergone an important boost as it makes it possible to acquire fundamental information directly at the crime scene, before starting the currently necessary sampling, custody and pre-treatment procedures. In addition, these characterizations are not destructive, nor do they modify the analyzed sample. These two aspects are peculiar in forensic investigations as they make it possible to ensure the objectivity of the experimental evidence even by non-specialized, but simply trained, personnel. Traces of human blood are among the most important evidences in criminal investigations. Blood samples have to be identified and collected immediately without contamination in the crime scene. Fonseca and coworkers evaluated the possibility to unambiguously identify human blood in stains found in floor tiles by handheld NIR spectroscopy. Authors reported that hierarchical models result in a significant scientific improvement useful for the identification of human blood stains at crime scenes (Fonseca et al., 2022).

Criminals often use common household cleaners, that are strong corrosive solutions, such as, in order to stun the victim. NIR handheld spectrometer was demonstrated to determine corrosive solutions through plastic bottles. Morillas and Frascione evaluated corrosive and harmless substances, to test the real NIR performance. Each predictive model identified the corrosive substances, enhancing the ability of this technique to pre-screen corrosive substances (Morillas and Frascione, 2022).

A modular handheld Vis-NIR spectrophotometer collected spectra from ink signatures by different ball-point pens, as a non invasive tool for ink identification in forensics (Ristova et al., 2022). As new approach in forensic chemistry, NIR/Chemometrics was proposed for the characterization of toners when questioned documents examination is requested (Materazzi et al., 2017b; Risoluti et al., 2018a).

It was proposed to solve illicit drug analysis by an ultra–portable NIR linked to a mobile application, demonstrating the possibility to display the result within 5 seconds (Coppey et al., 2020).

Determination of explosives was reported by Risoluti et al. on human hands using handheld MicroNIR (Risoluti et al., 2018b) and by Santonocito et al. using an optical array (Santonocito et al., 2022).

8 Applications to textiles

Textiles are daily used by all the people in the world. Especially in high fashion, quality and price can greatly change and often it is not easy to identify genuine products only by visualization. The possibility to easily characterize textiles allows to warrant consumers. Textiles are characterized by obvious differences in raw materials (wool, cotton, synthetics) but often small differences (blended versus pure filaments or the optimization of the appearance of polyester versus cotton) can result in significant quality assurance issues. NIR spectroscopy has demonstrated considerable potential in component characterization and feature differentiation.

Handheld NIR was proposed as good solution to textile authentication and identification by Yan et al. who demonstrated to be simply the comparison with reference spectra. PCA combined with SIMCA resulted the best discrimination models (Yan and Siesler, 2018).

Silk is a precious textile not only because of its physical and chemical properties, but also for its beauty. Cotton or polyester are the mainly mixed fibers to optimize the best look (Kumagai et al., 2004). Being not easy the distinction of silk blends from pure silk, portable NIR was tested for a fast characterization of dress composition, including a quantitative answer (Liu et al., 2013; Guifang et al., 2015). The silk was also blended with polyester and fully characterized by PLS calibration (Yan et al., 2020).

Identification of ancient textile fibers becomes fundamental for conservation of textile relics. Fiber identification methods require sampling and slicing cultural relics for observation under an optical microscope or a scanning electron microscope. Handheld NIR was applied to the identification of fibers from four Qing Dynasty textile relics, and resulted in a good spectral comparison (Li et al., 2021; Ding et al., 2021).

9 Applications to materials

Benchtop and handheld molecular spectrometers have been successfully applied in material identification. Compared to FT-MIR spectra, near infrared profiles allow to complete informations and often solve problems by simply comparing characteristic profiles instead of single band interpretation and assignment.

"To recycle" will be a must for the next generations. Great impulse is actually given to recycle the most common polymers. Handheld NIR was demonstrated to be a very easy-to-use tool to classify them with the aim of a safe recycle (Xiong et al., 2016).

Eder and coworkers described and discussed the possibility to use and transfer analytical techniques, including NIR, for in-field characterization of photovoltaic modules. Polymeric compounds of the photovoltaic modules were analyzed and characterized without modules dismantling, transporting into the lab, cutting and analyzing in conventional bench-top spectrometers (Eder et al., 2020). Catauro et al. characterized bioactive ferrous citrate–silica hybrid materials obtained by a sol–gel synthesis.

10 Applications to wood, cellulose, lignin and lignite

Wood species can be identified by Vis-NIR spectroscopy: this approach is based on light absorption scattering due to the wood characteristics. However, innovative methodologies based on diffuse reflectance demonstrated the possibility to classify many different woods and portable NIR instruments can be easily used for in-field characterizations.

A handheld Vis-NIR system was realized and, to simplify the interpretation of the spectra, wood classification was obtained by PCA scores (Ma et al., 2021b). The development of a low-cost handheld spectrometer to detect wood defects was proposed by (Sandak et al., 2020).

Characterizations from a standing tree minimize and optimize the time requested since eliminate the transport, the transformation in powder and the storage. Ramadevi et al. (2022) estimated the yield of Kraft pulp by portable NIR spectrometer. A fast characterization of holocellulose and lignin in wood by Kernel extreme learning machine was proposed by (Yang et al., 2020).

Off-line determination of diverse wood quality aspects by a portable NIR sensor was demonstrated by Sandak et al. in glue-laminated timber. The chemometric model specifically developed was demonstrated to be helpful in prediction of the total delamination and detailed delamination length (Sandak et al., 2021).

Three moisture predicting models in Para rubber timber were proposed by Noypitak et al. The handheld NIR spectrometer coupled to a smartphone facilitated the quantification of real-time moisture content. An android application was specifically settled up to manage the instrument. Unknown samples allowed to validate the rsults from the predictive equation (Noypitak et al., 2022). A similar approach was proposed by Puttipipatkajorn (Puttipipatkajorn and Puttipipatkajorn, 2020).

Lim et al. proposed to determine the densities of cross linking in latex by an innovative method based on portable NIR (Lim et al., 2021).

11 Applications to natural extracts

Natural extracts can result in complex mixtures with unknown composition if by-products or contaminations are not monitored and eventually eliminated through subsequent purifications. Consumer protection therefore becomes fundamental both for the bodies in charge of surveillance and for the producer who, in self-protection, controls his own product. Zhuang et al. proposed a quantitative model to monitor active components in Radix Astragali extract. The quantitative model was stressed by comparing a usual FT-NIR with a portable NIR. PLSR models indicated that the calibration model can significantly improve the adaptability to new samples (Zhuang et al., 2022).

The market of Turmeric is increasing since curcuminoids are recognized to give health benefits. Spectroscopic methods with chemometrics are able to quantify turmeric to control food quality and allow analysis speed, versatility, portability and no need of any pretreatments. Khongkaew et al. published a study with 5 calibration models for the quantification of curcuminoids in turmeric both by benchtop and portable instrument. The results indicated benchtop and portable methods in good agreement, confirming the suitability of portable devices in food quality control by analyses in situ (Khongkaew et al., 2022).

Menevseoglu proposed portable FT-NIR, FT-MIR, and Raman spectrometers to identify adulterations in black seed oil by. SIMCA and PLSR models were applied to predict the adulterant levels (Menevseoglu, 2022).

12 Other applications

12.1 Applications to cultural heritage

Cultural heritage is the field with the greatest application interest as the non-invasive and portability characteristics of spectroscopy fully embrace the needs of conservation and respect for works that continue over time to bear witness to the excellence of the past. For example, wall paintings are art works based on ancient technologies and materials typical of civilizations from the past. Imaging instrumentation allows the study of the materials and the characterization of pigments.

Asscher and Halevi presented comparative results by stationary or portable modified digital camera, showing the strong environmental influence on the image (Asscher and Halevi, 2022).

In the project "Leonardesque Artists beyond the Visible", non-invasive portable imaging and spectroscopic-based approach were proposed to obtain useful informations like the description of pigments composition, binder preparation and painters' technique identification. Results underlined a specific painting technique in each author (Galli et al., 2021).

12.2 Applications to geology

The characterization of mafic and ultramafic rocks is important to determine relationships with specific. Adams et al. demonstrated that the X-ray accurate determination can be completed by handheld VIS and NIR analysis (Adams et al., 2021).

12.3 Applications to waste materials

Plastic waste classification is fundamental to set the right recycle Diffuse reflectance spectra of several reference and commercial polymers allowed to give fast, nondestructive, in-site characterizations by applying different pretreatments. The results proved that PCA allows to separate different plastic materials (Yang et al., 2020).

12.4 Aquaphotomics

The spectrum of the water in aqueous systems gives information on covalent OH and hydrogen bonds since they are deeply influenced. In water NIR spectra, the information results as a function of internal and external factors. Aquaphotomics evaluates by near infrared spectra the groundwaters, not influenced by other factors like temperature or humidity.

Results published by Kovacs and coworkers demonstrated that groundwater samples give specific fingerprint and unicity of the spectroscopic profile that can be used as an indicator of water changes (Kovacs et al., 2022).

Soil-to-water ratios were calculated by Vis-NIR spectra to predict the electrical conductivity by (Gozukara et al., 2022)

A special issue, dedicated to aquaphotomics, was published in the open-access journal Molecules (Muncan and Tsenkova, 2023).

12.5 Applications to fuels

Systematic adulterations of gasoline, ethanol and diesel make fundamental the possibility to have analyitical tools,

able to determine fuel integrity. Tosato et al. (2020) characterized 115 seized fuels and proved the efficiency of portable near infrared spectrometers assiste by chemometrics. Diesel quality can be evaluated by the "condensation point". In-field fast determination of condensation point could minimize the costs. Wan et al. (2021) collected representative spectra using a handheld NIR to setup a prediction model.

Motor and crude oil can be improperly mixed, as found in Brazil by companies of energy sector. Santos and coworkers showed the possibility of handheld NIR spectroscopy to detect these frauds. Discrimination potential resulted in 100% of specificity and precision (Santos et al., 2021).

Environment protection pushes to renewable energies like bioenergy. Fuel surveillance to meet the european rules is consequently needed. Hand-held near spectroscopy was tested on wood chip samples. Results showed a satisfactory reliability because each measure is acquired in seconds and the non-destructive analysis allows to efficiently control fuel quality (Toscano et al., 2022). Pellet recently was studied because of its storage cost and combustion efficiency. The possibility to trace pellet quality is important, since fraud behaviors could impact consumers' health. Usual pellet analyses are costly and time-consuming Mancini and coworkers defined a handheld-NIRs approach to propose a fast and automatic classification of pellet (Mancini et al., 2020).

12.6 Applications to micro- and nano-materials

Orsi et al. setted up and calibrated a handheld NIR method to determine ROS, because of its impact in Photodynamic therapies. The approach is based on the fluorescence emission in the near-infrared spectral range at $\lambda = 1,270$ nm. Several nanostructures have been proposed as able to produce reactive oxygen species voted to medicine therapies (tumours in deep tissue) (Orsi et al., 2022).

Microplastics residues are a growing environmental problem. A review proposed by Tirkey and Upadhyay collected and highlighted innovative approaches in microplastics sampling and identification, including NIR (Tirkey and Upadhyay, 2021).

12.7 Applications to asphalt

Modern asphalts are often the result of modifiers inclusions. These modifiers increase sustainability, lower rutting and low-temperature cracking. To this end, a portable molecular sensing technology was proposed, consisting in a pocket-sized near-infrared molecular sensor, able to detect recycled materials. It was demonstrated that the resulting fingerprint of the bituminous materials helps the classification (Jahangiri et al., 2021). The same authors proposed a smartphone-based approach (Barri et al., 2020).

13 Chemometrics

Private companies always more ask for on-site analysis by portable instruments, better if spectroscopic devices. Schoot et al. presented a new prediction model from portable NIR data to predict protein content in pig feed (Schoot et al., 2022).

With increasing availability of handheld NIR spectrometers, is of interest the possibility to transfer calibration model from benchtop to portable NIR. Rukundo and coworkers calibrated a benchtop NIR and transferred calibrations to a benchtop and portable instruments. Model transferring however was not direct and required data treatments (Rukundo et al., 2022).

Advantages in milk analysis by NIR spectrometers was proposed by (Said et al., 2022).

Various preprocessing techniques and their combinations were comparatively proposed by Sarkar et al. to quantify soluble solids in kiwi fruits (Sarkar et al., 2020). The content of dry matter when harvesting was proved to have correlation with soluble solids in Kakadu plum samples (Bobasa et al., 2021). De Freitas and coworkers (de Freitas et al., 2022) and Wokadala and coworkers (Wokadala et al., 2020) determined the fruit dry matter content at harvest in Brazil, while the detection of internal physiological disorders was determined by (Mogollón et al., 2020). Portable optical instruments were specifically studied to determine fruit ripeness (Abasi et al., 2021), even directly on the by McCormick and Biegert (McCormick and Biegert, 2021). Pissar et al. (2021), (Zhang et al., 2022; Zhang et al., 2022), (Guo et al., 2020) and (Fan et al., 2020) described the usefulness of a portable NIR to determine apple quality.

Yang et al. (2022) and (Yu et al., 2021b) determined soluble solids content in pears based on VIS-NIR and model analysis and variable selection. Wu et al. (2021). settled up a non-destructive characterization of pears by a home-made NIR and a chemometric prediction model. Mulisa Bobasa and coworkers evaluated 4 different positions to achieve NIR spectra of Kakadu plum fruits, thus monitoring fruit chemical composition (Mulisa Bobasa et al., 2020). The nonlinear optical properties of monodispersed diphenylpolyynes were also studied by (Fazio et al., 2014).

Xiao and Chen presented an innovative research on NIR data analysis by using Machine Learning algorithms to study *in-vivo* the human skin characteristics. NIR showed sure potential to develop a cheap, handheld and powerful, skin characterization tool (Ca et al., 2018; Scala et al., 2018; Risoluti et al., 2020h; Xiao and Chen, 2022).

Author contributions

SM and RR wrote the manuscript. GG, LB, and EP searched for references. AG supervised the search. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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