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The size distribution metrics and kinetic energy of raindrops above and below an isolated tree canopy in urban environment

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ABSTRACT

Raindrop impact on bare soils is the initial phase of rainfall-induced soil erosion which is altered under any type of vegetation due to the interactions of rainfall with the canopies. This study examines the drop size distribution (DSD) and kinetic energy (KE) of raindrops above and below the birch tree (*Betula pendula Roth.*) canopy in a research plot in the city of Ljubljana, Slovenia using a one-year observation of 63 rainfall events and the effect of meteorological variables under moderate continental climate. Simultaneous measurement of the microstructures of open rainfall and throughfall was carried out using an optical disdrometer. The result of our analysis revealed that throughfall DSD showed two distinct major peaks (bimodal) occurring primarily on smaller drop sizes while open rainfall has only one. The cumulative drop number, median drop-volume diameter (D_{50}), and drop fall velocity of throughfall were 16.4%, 26.6%, and 5.0% lower than those of open rainfall, respectively. Also, the relative volume percentage of raindrops > 1.5 mm is 1.5 times higher than those observed in throughfall drops which indicates that the presence of the canopy caused the fractionation of larger drops into smaller droplets. These reductions significantly differ depending on the phenoseasons of the canopy with the leafed state being higher than the leafless state. Similarly, the Kruskal-Wallis H test result revealed that birch tree elicits a statistically significant change in the kinetic energy of open rainfall, thus weakening the mean rainfall KE by 33.7%. On the other hand, KE is positively affected by the phenological condition of the canopy with higher attenuation being observed during its leafed state. Also, the correlation analysis demonstrated that vapor pressure deficit, air temperature, and relative humidity have stronger associations with throughfall kinetic energy among meteorological variables considered. These findings underscore the necessity of an optimized selection of tree species for afforestation programs.

1. Introduction

Soil erosion is a complex process encompassing detachment, transport, and deposition of soil mass (Holz et al. 2015; Rodrigues et al. 2020; Yulianti et al. 2020) caused by the dynamic activity under the gravity of causative agents such as water, snow, ice, wind, and mass movement. It is a naturally occurring phenomenon responsible for soil formation (Pathirana et al. 2009) which is accelerated by anthropogenic forces (i.e., unsustainable land use, intensive agriculture, deforestation) causing social, economic, and environmental consequences worldwide (Almagro et al. 2017). It seriously affects the essential ecological functioning of soil: food production for humans and animals; capacity to filter, buffer and transform materials that circulate in the biosphere; and biological habitat for living organisms (Blum et al. 2006). In this sense, soil erosion is an important matter from ecological and economic points of view (Geißler et al. 2012a,2012b). One of the principal drivers that affect the energy balance of soil erosion processes is rainfall (Sukhanovski et al. 2002) where the direct impact of raindrops on the soil surface is the initial phase of water-induced erosion. Raindrop triggers the dislodgment of soil particles, dispersion of aggregate materials, and transport of eroded sediments (Foot and Morgan, 2005; Nanko et al. 2020; Pathirana et al. 2009). Soil movement by rainfall is usually at the greatest and most noticeable during short-duration, high-intensity storms (Janapati et al., 2019). This potential ability of rainfall to cause soil erosion and transport by raindrop impact is termed erosivity (Angulo-Martínez et al., 2016). Rainfall erosivity is generally characterized by the kinetic energy and momentum of raindrops (Goebes et al. 2014; Foot and Morgan, 2005; Nanko et al. 2008) which are a function of drop characteristics (mass, size, shape, terminal velocity, and drop size distributions) and rainfall intensity (Shinohara et al. 2018). Momentum measures the

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forces exerted by the raindrops on soil which induces mechanical stress that leads to soil aggregate breakdown. On one hand, the kinetic energy of rainfall is a major factor initiating soil detachment (Carollo et al. 2018; Lal, 1994) which requires the analysis of raindrop size distribution and terminal velocity (Jan and Jana, 2018). The kinetic energy of raindrops is transferred to soil particles, causing splashing and initiating soil erosion due to disaggregation and mobilization of the soil particles (Wang et al. 2014). Moreover, as these parameters are chiefly dependent on rainfall characteristics, the severity of rainfall-driven soil erosion is expected to increase as a consequence of the increasing frequency and magnitude of precipitation due to climate change. This additional pressure calls for adequate and sustainable soil protection and conservation practices in the framework of ecosystem management (Panagos et al. 2015; Rodrigues et al. 2020). Thus, afforestation is widely recognized as a common measure to reduce and control soil erosion (Li et al. 2019; Nanko et al. 2008; Panagos et al. 2015; Rodrigues et al. 2020) which is also an essential climate change mitigation strategy (Forster et al., 2021).

Trees are important modulators of biosphere-atmosphere interactions (Levia et al. 2017), which have a sphere of influence on the ecosystem's hydrological processes and resultant water availability and quality (Rodrigues et al. 2020). With the interception and retention of precipitation by forest canopies, trees are able to regulate the quantity, intensity, and spatiotemporal variability of throughfall - the fraction of rainfall that reaches the forest floor by passing directly through the canopy or dripping from vegetative surfaces (Levia et al. 2017). It constitutes the majority of incident precipitation reaching the ground with different drop size distribution (DSD), drop velocity, and kinetic energy (KE) from open rainfall owing to the interactions with plant canopies (Levia et al. 2017; Nanko et al. 2020). The key determinants influencing the DSD and KE of throughfall include abiotic (i.e., rainfall characteristics, meteorological conditions, season) and biotic (i.e., tree height, canopy structure, leaf area index, crown density, phenology, etc.) factors (Levia et al. 2017). Throughfall sometimes consists of larger drops compared to rainfall because of the dripping effect from the coalescence of raindrops on the plant surface which attains greater momentum and kinetic energy with growing canopy height (Chapman, 1948; Nanko et al. 2020; Shinohara et al. 2018). Nanko et al. (2006) found that the development of throughfall DSDs in coniferous forests was smaller than in deciduous ones because of the less storage capacity of needles compared to broad leaves. Furthermore, the DSD of throughfall was mainly affected by the presence and absence of foliage in a study conducted by Nanko et al. (2016) on a yellow poplar (*Liriodendron tulipifera L.*) in Maryland, USA. Zabret and Šraj (2018) found that the microstructures of rainfall also induced an influence on the spatial variability of throughfall under a single birch tree in addition to phenology and rainfall amount. While in particular, throughfall kinetic energy (TKE) is used as an indicator to express and evaluate the erosive power of rainfall under the canopy which is necessary for the prediction of soil erosion in forests (Goebes et al. 2015a; Liu et al. 2018a,2018b; Nanko et al. 2020). In addition to this, TKE is also demonstrated to have spatial variability (Geißler et al. 2012a,2012b; Goebes et al. 2015b; Liu et al. 2018a,2018b; Nanko et al. 2011,) which is an inherent characteristic of throughfall. Though it is normally believed that the occurrence of soil erosion is generally reduced and/or controlled in forested areas (Geissler et al., 2010; Hill and Peart, 1998; Morgan, 2009), several studies have found that TKE can be higher in forests even with a well-developed canopy than in the open field (Geissler et al., 2010; Liu et al. 2018a,2018b; Nanko et al., 2004; Nanko et al., 2008; Zhou et al., 2002). This observation is attributable to high amounts of bare ground due to the absence of leaf litter cover and understory vegetation which are one of the causes of severe soil erosion observed in some forests (Geissler et al. 2010; Goebes et al. 2015b; Shinohara et al. 2018). For instance, Liu et al. (2018a,2018b) showed that the TKE under a rubber monoculture was 2.32 times higher than the KE of open rainfall but it was significantly reduced to 1.84 by the presence of multiple understory canopies in rubber-based agroforestry systems. The results of Geissler et al. (2010) indicated that the erosive power of throughfall drops is 2.59 times higher than the raindrops in the open environment in which they associate this potential as a function of stand height and age of forest stand. Also, the findings of Lacombe et al. (2018) revealed that higher canopies with larger leaves increase the KE of throughfall due to larger drop sizes, but the low and dense understory vegetation reduces the velocity and maximum diameter of throughfall resulting in lower values of TKE.

While there exist several studies on throughfall have been conducted, the call for throughfall DSD and kinetic energy studies has progressed increasingly with the need for a detailed understanding of forest water balance and soil erosion mechanisms (Nanko et al. 2013). It is of vital importance to expand this understanding in different geographic settings, climatic conditions, and types of tree species. The assessment of Zore et al. (2022) revealed that the rainfall interception by a single birch tree reduced the kinetic energies of below-canopy raindrops by 30% and 3% during the leafed and leafless periods, respectively. Consequently, there is a reduction of 21% and 50% in the rainfall erosivity factor during the respective phenoseasons. Although the studies of Zabret et al. (2018) and Zabret and Šraj (2021a) reported rainfall microstructures as one of the determining factors that influence rainfall interception, a simultaneous measurement of drop number, diameters, and fall velocities of rainfall and throughfall are still rarely included in ecohydrological studies. As a follow-up to the aforementioned studies, the present research examines the details of DSD metrics and kinetic energy of raindrops above and below the birch tree canopy in different phenoseasons (leafed and leafless states) using an optical disdrometer. This will improve the underlying knowledge of the erosional processes and potential beneath a deciduous canopy, especially that afforestation is one of the primary measures to control soil erosion. On the other hand, the DSD of rainfall is among the determining factors of raindrops' erosive potential (Shinohara et al. 2018; Torres et al., 1992) and it also plays a role in how trees could function in controlling the mechanisms of rainfall-induced soil erosion. In addition to this, Levia et al. (2017) mentioned, there is limited work concerning the effects of meteorological conditions on throughfall drop sizes compared to the influence of plant morphology and canopy structure (Levia et al. 2017). Thus, this study specifically investigated (a) how the phenological conditions of trees affect the DSD and KE of throughfall and (b) the association of the KE of raindrops above and below the canopy with the local meteorological conditions.

2. Materials and methods

2.1. Study area

The study was conducted in an experimental site in the city of Ljubljana, Slovenia (46.04° N, 14.49° E, 292 m a.s.l., Fig. 1). The study area is characterized by the moderate continental climate of central Slovenia with clearly defined seasons (Ogrin, 1996). Slovenia, in general, is potentially threatened by water erosion due to the irregularity of relief and abundance of rainfall, but its occurrence is momentarily controlled by the high proportion of forest covers (Hrvatin et al. 2006; Repe, 2004). Ljubljana lies in a basin surrounded by low hills and is covered with 46% of natural forests (ICLEI, 2022). Due to its location inside the basin, a temperature inversion is a frequent occurrence and the average annual temperature was 11 °C. According to the long-term measurements (1986–2016) at the Ljubljana Bežigrad meteorological station, the annual average precipitation in the area is 1355 mm, with autumn being the wettest season (439 mm), followed by summer (384 mm), spring (289 mm), and winter (243 mm).

2.2. Experimental set-up and measuring equipment

The microstructures of rainfall and throughfall beneath a birch tree

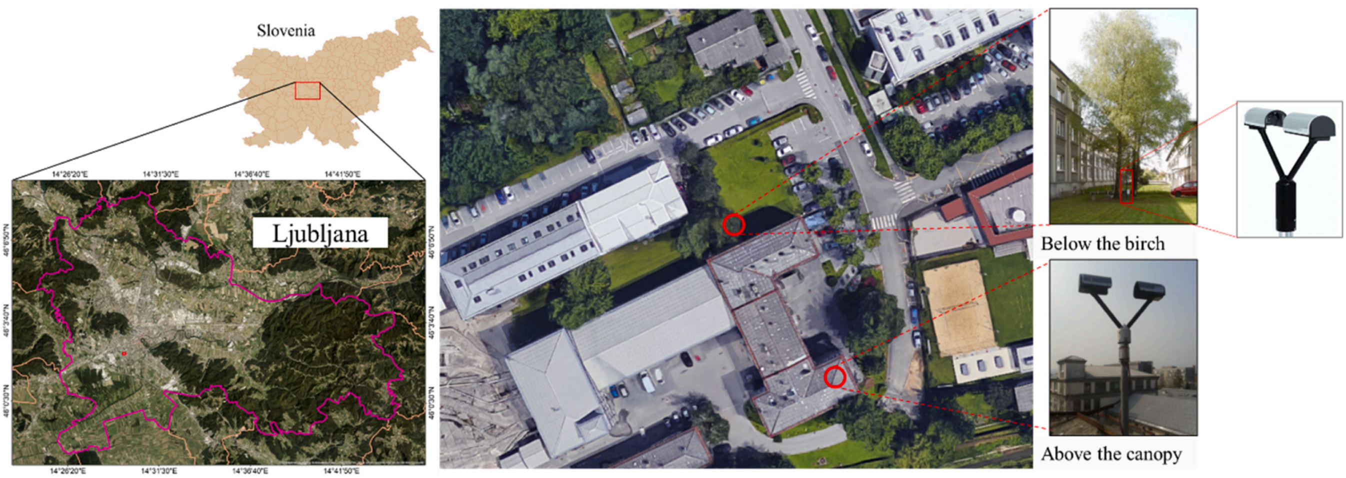

Fig. 1. Location of the study site and optical disdrometers above and below the birch tree canopy.

canopy (*Betula pendula Roth.*) were measured simultaneously by a pair of OTT Parsivel optical disdrometers (Fig. 1). The above-canopy disdrometer was mounted on the rooftop of the nearby 14.45-m high building (45 m away from the tree) to measure the raindrops outside the canopy. The other disdrometer was positioned below the tree canopy and ~1.8 m above the ground to sample throughfall drops. The experimental birch tree has a canopy projection area of 20.3 m^2, a diameter at breast height of 18.3 cm, an average height of 16.2 m, a canopy base height of 2.8 m, and an upward branch inclination of 53.3° (Zabret and Šraj 2021b). Birch trees have distinct four canopy phenoseasons, namely leafed, leaf-fall, leafless, and leafing which are defined according to the measured leaf area index. Since only a few events occurred during the shorter periods of leaf-fall and leafing, we decided to divide the observation period into two phenoseasons; leafed and leafless. The leaf area index of the investigated birch tree measured with the LAI-2200c sensor (LAI-2200 plant canopy analyzer, Li-Cor Inc., Lincoln, NE, USA) was 2.6 and 0.8 during the leafed and leafless periods, respectively (Zabret et al., 2018; Zabret and Šraj, 2021a). The common birch is a deciduous tree with an irregular crown and the leaves are glabrous, simple diamond-shaped, 4–7 cm long and 2–4 cm wide. They are naturally distributed in Slovenia and can also be found all over Europe, except in Spain, Portugal, and Greece (Kotar and Brus, 1999).

The Parsivel disdrometer measures the microstructure of rains, such as the diameters, falling velocities, and the number of raindrops at 1-minute intervals. It is a laser-based optical sensor with a measuring area of 54 cm^2 that can record particles from a diameter of 0.2 mm and precipitation lower than 0.01 mm/hr. The measured particles at a 1-min resolution are stored into a matrix of 32 drop diameter classes (ranging from 0.062 mm to 24.5 mm) x 32 velocity classes (ranging from 0.05 m/s to 20.8 m/s) bins. The first two diameter classes, which have a size smaller than 0.25 mm, are always forced to zero by the manufacturer since they are outside the measurement range of the device due to the low signal-to-noise ratio (OTT, 2008). It should be emphasized that we used the measured data from an OTT Parsivel disdrometer, as estimates of the size distribution of raindrops depend on the instrument used; for example, OTT Parsivel, POSS, LPM300, or 2DVD can differ from each other (Petan et al. 2010; You, Lee, 2015; Park et al. 2017). We also assumed in our analysis that raindrops with a diameter larger than 7 mm were excluded from the measured DSD. This was implemented to minimize the effect of measurement errors of the instrumentation (Nanko et al. 2016; Petan et al. 2010) that occur when the disdrometer detects two or more coincident raindrops falling through the measuring area (or laser beam) simultaneously as one large raindrop (Bezak et al., 2021), which can cause overshooting of the peak intensities (Lanzinger et al. 2006). Also, samples with a disdrometer-derived 1-minute rainfall intensity of less than 0.1 mm/h were regarded as noise and excluded from the analyses (Petan et al. 2010; Zhang et al. 2019). Additionally, due to the limited number of disdrometers, the following setup was not able to capture the spatial variability of throughfall under the canopy as the disdrometer was installed in a fixed position throughout the study period. Its position is neither directly under a large branch nor in an open gap, such that, the micro-location of the disdrometer at the middle between the trunk and edge of the lower canopy was selected as representative as possible for the throughfall drop measurement in birch tree. Our measurement setup also did not consider the inherent heterogeneity and variation in the canopy cover of the birch tree. Thus, these aspects are well-acknowledged as part of the limitations of our study. The focus was rather laid on the changes of DSD and KE of rainfall due to tree canopy in different phenoseasons (leafed and leafless) and their association with the meteorological variables.

Auxiliary measurements include monitoring of rainfall characteristics under natural conditions and throughfall amounts under the birch tree canopy. An automatic 0.2-mm tipping-bucket data-logging rain gauge (Onset RG2-M) was mounted in the clearing of the research plot. Whereas throughfall was measured with 10 roving funnel-type and 2 fixed V-shaped steel trough gauges. One trough collector is equipped with a tipping bucket flow gauge (Unidata 6506 G; 50 ml/tip) and automatic data logger (Onset HOBO Event), while the other one is connected to polyethylene containers from which the data are collected manually after every rainfall event along with the roving gauges. Hereafter in this paper, the term gauge-based or gauge-measured was used interchangeably to refer to these auxiliary measurements.

2.3. Data analyses

Independent rainfall events were separated by at least a 4-hour minimum inter-event dry period, as suggested by Zabret and Šraj (2021a) for this region and for the birch tree canopy. During the observation period, 63 rainfall events with throughfall occurrences were recorded from August 2021 to August 2022 covering the leafed and leafless periods of birch tree. Prior to the analysis, additional filtering of data was employed by excluding rainfall events that were influenced by snow and with less than 2 mm of total rainfall depth. While additional in situ meteorological parameters used in the analysis, including average relative humidity (R_h, %), air temperature (Temp, °C), wind direction (W_d, °), wind speed (W_s, m/s), and maximum wind gust (W_g, m/s), were obtained from the meteorological station in Ljubljana Bežigrad, operated by the Slovenian Environment Agency (ARSO). These data were available in 10- and 30-minute temporal resolution in ARSO archives. According to its location in the Ljubljana basin, its data are representative of the entire area and the outskirts (Nadbath, 2008; Zabret and

Šraj, 2021a). Vapor pressure deficit (VPD) was derived using the information of air temperature (°C) and relative humidity (%), calculated as the difference between saturation vapor pressure, e_s and actual vapor pressure, e_a (VPD = $e_s - e_a = e_s - (\mathrm{Rh} - e_s/100)$) (Monteith and Unsworth, 2013). e_s (kPa) was then calculated using Teten's formula (Eq. 1) as provided by Monteith and Unsworth (2013).

$$e_s = 0.61078 * \exp\left(\frac{17.27 * Temp}{Temp + 237.3}\right) \tag{1}$$

Using the disdrometric data on drop sizes and velocities, the drop size distribution and several characteristics of rainfall can be obtained. In this study, we focused on the median drop-volume diameter (D_{50}) and kinetic energy of open rainfall and throughfall. The DSD of open rainfall and throughfall were expressed based on drop relative volume ratio, V (D) in Eq. 2 which has been generally used in throughfall studies (Levia et al., 2017). According to Sempere-Torres et al., (1998), D_{50} is also often used to represent the entire DSD and it has been used to observe the throughfall DSD beneath different canopy species (Hall and Calder, 1993; Levia et al., 2019; Nanko et al., 2006). Thus, we obtained the D_{50} according to the formula used by Nanko et al. (2016) in Eq. 3.

$$V(D) = \frac{\sum_i^c n_i V_i}{V_{total}} \tag{2}$$

$$D_{50} = D_{m1} + \frac{\frac{1}{2}\sum_i^c n_i V_i - \sum_i^{m1} n_i V_i}{\sum_i^{m2} n_i V_i - \sum_i^{m1} n_i V_i}(D_{m2} - D_{m1}) \tag{3}$$

where c is the number of raindrop class diameter, n_i is the number of detected drops per diameter class, V_i is the raindrop class volume $\left(\frac{\pi}{6}D_i^3\right)$ assuming spherical drops had passed through the measuring area, V_{total} is the cumulative volume of all drops (mm^3), D_{m1} and D_{m2} are the raindrop class diameters with cumulative raindrop class volumes less than (m_1) and greater than (m_2) 50% of the total raindrop volume, respectively.

While the kinetic energy per area (J/m^2) of rainfall in natural conditions and throughfall under the birch tree canopy was computed using the formula (Eq. 4) from Petan et al. (2010).

$$KE = \frac{\rho\pi}{12 \bullet 10^3 A} \bullet \sum_i n_i \frac{1}{D_{b,i} - D_{a,i}} \int_{D_{a,i}}^{D_{b,i}} D_i^3 dD \bullet \frac{1}{v_{b,i} - v_{a,i}} \bullet \int_{v_{a,i}}^{v_{b,i}} v_i^2 dv \tag{4}$$

where n_i is the number of detected raindrops in the size class i, D_i (mm) is the drop class diameter ranging from $D_{a,i}$ to $D_{b,i}$, ρ is the density of water (kg m^3) and v_i (m/s) is the raindrop fall velocity of class i ranging from $v_{a,i}$ to $v_{b,i}$. The kinetic energy of open rainfall (above the canopy) is referred to as OKE (open kinetic energy) and throughfall (below the canopy) is TKE (throughfall kinetic energy).

Statistical analyses of data were carried out in R software version 3.3.0 + (R Core Team, 2021). First, the normality of the distribution of kinetic energies below the birch tree canopy was evaluated using the Kolmogorov–Smirnov test. As the normal distribution was not satisfied, the non-parametric Kruskal-Wallis H test was employed to assess the potential significant difference between the kinetic energies of open rainfall and throughfall and between phenoseasons. The association of the kinetic energies (OKE, TKE), D_{50}, and drop relative volume ratio with the selected meteorological variables was statistically assessed using correlation analysis. The significance level was set to 0.05.

3. Results and discussions

The total amount of rainfall recorded by the tipping-bucket rain gauge (0.2 mm/tip) in the nearby clearing of the research plot for the considered 63 rainfall events was 922.8 mm. These events produced a cumulative throughfall of 688.5 mm (74.6% of the total open rainfall) which was obtained from manual and automatic throughfall collectors (Section 2.2). In particular, 52% of the accumulated gauge-based throughfall volume was collected from 24 rainfall events (total rainfall = 444.2 mm) during the leafless condition of the birch tree canopy and 48% of which was registered from 39 events (total rainfall = 478.6 mm) in the leafed period (Fig. 2a). The amount of delivered rainfall within the investigated period was lower compared to the values reported by Zabret and Šraj (2021a) for 2014–2016 and by Zore et al. (2022) for 2017–2018. Thus, it is worth mentioning that in the span of our observation period, there was a winter-spring precipitation deficit in Slovenia at the start of 2022, which was aggravated by severe drought conditions during summer (ARSO, 2022). Over the measured period, the event rainfall depth varied from 2 to 87.6 mm with a 50th percentile event of 8.4 mm. Meanwhile, the 95th and 98th percentile rainfall events were found to be 44.8 and 76.5 mm, respectively.

Furthermore, we found that the above-canopy disdrometer mostly overestimated the total rainfall amount of all events with a mean overestimation of 10.4% compared to rain gauge measurement. Whereas disdrometer-derived amount of throughfall is nearly equal to the gauge-based measurement with a percentage difference of 1.1%. As a consequence, the ratio of throughfall to open rainfall based on disdrometer data is on average lower than the ratio obtained from gauge-measured data (Fig. 2b). One reason for this observation comes from the overestimation of the total rainfall amount by the disdrometer which was also reported in other studies (Bezak et al., 2021; Petan et al., 2010; Zore et al., 2022). And since disdrometer-derived rainfall/throughfall amount is a function of drop numbers, Upton and Brawn (2008) reported that the earlier version of the Parsivel optical disdrometer had a tendency to overestimate the number of drops bigger than 2 mm. Nevertheless, we observed a very strong correlation between the disdrometer-derived and gauge-based throughfall/open rainfall amount. Also, regardless of the measuring instrument, the amount of throughfall exhibits a significant linear increase with increasing open rainfall ($R^2 = 0.97$, $p < 0.001$) over the events measured, indicating a positive association between the two variables.

Approximately 7.9×10^6 raindrops were captured by the disdrometer above the canopy for the observed number of rainfall events with a total number of drops per event ranging from 3408–648,733. Whereas the disdrometer beneath the birch tree canopy recorded a total throughfall drop count of about 6.6×10^6, ranging from 7325–523,559 drops per event, 16.4% less than those above the canopy (Fig. 3a). The same observation was also reported in some studies regarding the fewer drop number in throughfall compared to open rainfall owing to the effect of canopy interception (Brasil et al., 2022; Li et al., 2019; Lüpke et al., 2019; Nanko et al., 2004; Zore et al., 2022). However, they found that some individual events have a greater number of drops under the canopy which indicates that throughfall DSD significantly varies within rainfall events. Additionally, a 48.9% reduction in the cumulative volume of drops was also observed across all rainfall events owing to the interception process by the birch tree canopy. The cumulative number (Fig. 3a) and volume (Fig. 3b) of drops above and below the canopy vary significantly according to the condition of the canopy with the leafless season being higher than the leafed season. However, due to the fractionation of larger drops into smaller droplets caused by the presence of leaves in the canopy, we can observe a higher number of throughfall drops (11.7% more) compared to that of open rainfall during the leafed period. While in the leafless period of the birch tree, only the tree skeleton (e.g., branches, twigs, limbs) can directly influence the drops falling through the canopy with more gaps to penetrate which yields a throughfall drop count that is 29.1% less than that of open rainfall. This occurrence is the reason why drop sizes of < 1.5 mm, which are mostly categorized as the splash throughfall (Nanko et al., 2016), constitute 89.8% of the total number of drops below the canopy and 41.8% by volume. In addition, the relative volume percentage of drops > 1.5 mm for open rainfall across all events is, on average, 1.5 times higher than

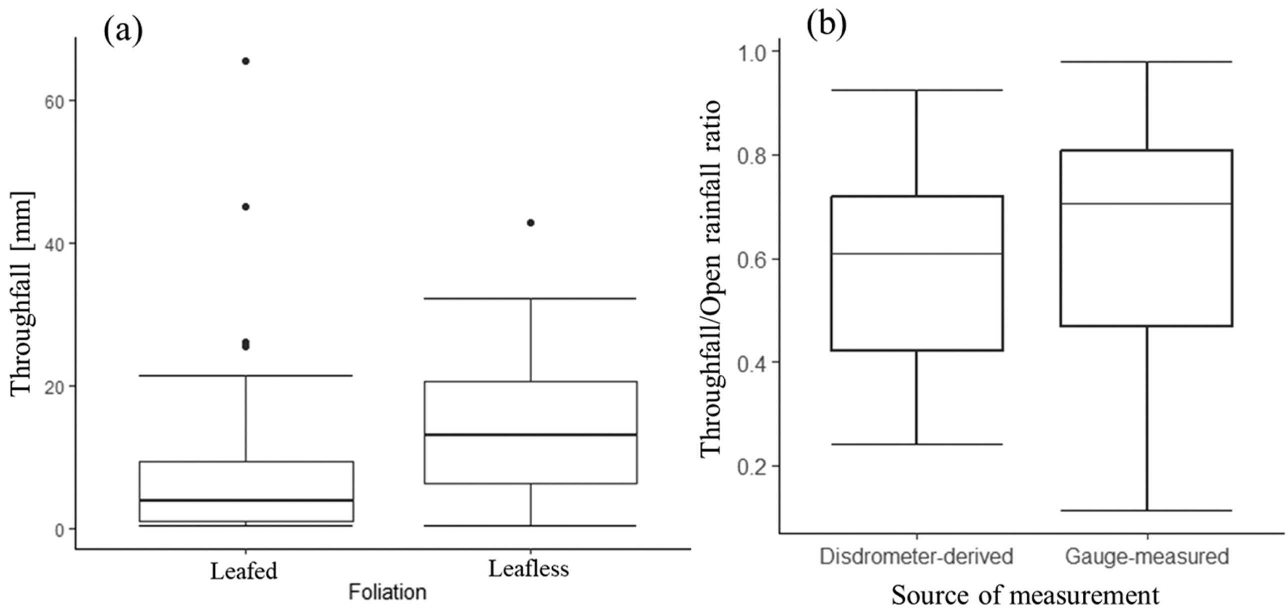

Fig. 2. Boxplots of (a) throughfall amount during leafed and leafless periods and (b) the ratio of throughfall to open rainfall based on disdrometer and gauge measurements.

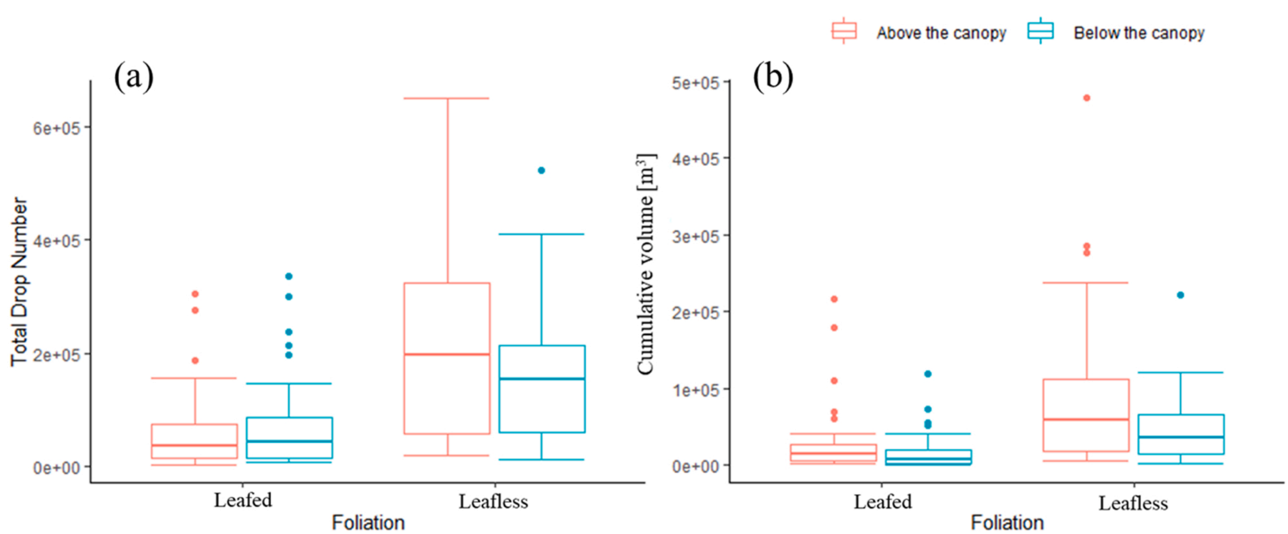

Fig. 3. Boxplots of the (a) total number of drops and (b) cumulative drop volume above and below the canopy in leafed and leafless periods.

those observed in throughfall. While in the context of throughfall components, these drops with a diameter > 1.5 mm is classified as canopy drip (Levia et al., 2017; Nanko et al., 2016; Nanko et al., 2006) with a smaller share of relative volume ratio in the leafed period compared to the leafless period (Fig. 5a). Hence, the presence of foliage facilitates the occurrence of splashing in the event of rainfall which explains the high concentration of throughfall drops < 1.5 mm. Such observation is reflected in the DSD of open rainfall and throughfall which is based on the drop relative volume ratio (Fig. 4).

Fig. 4 depicts the DSD of open rainfall and throughfall during leafed and leafless periods based on the relative drop volume ratio. Throughfall has a bimodal DSD regardless of phenoseasons with two distinct peaks occurring at drop sizes of 0.937 and 1.375 mm and open rainfall typically follows a unimodal DSD (Levia et al., 2017; Li et al., 2019; Nanko et al., 2004). We can observe that the modes of the DSD for both phenoseasons are quite similar with the unimodality of open rainfall being more evident during the leafed season (Fig. 4a). But in this study, we found two peaks in open rain spectra during the leafless season (Fig. 4b) with 1.375 mm as the most frequently occurring drop diameter and the lower peak may be caused by the averaging process which was also observed by Lüpke et al. (2019). Drops exceeding 1.375 mm in diameter comprised 49.6% of the precipitation and 28.9% of the throughfall by volume. The relative volume of drops larger than 3 mm represented 31.4% and 14.3% of the cumulative drop volume of open rainfall and throughfall, respectively without considering the differences in phenoseasons. However, it is worth mentioning that these drops contributed only 0.3% and 0.1% to the total drop numbers of open rainfall and throughfall, respectively. This further supports that the volume of raindrops and throughfall drops was more governed by the drop diameter than the drop number which was also described by Brasil et al. (2022) and Li et al. (2019). On the other hand, Nanko et al. (2004) found that open rainfall consists primarily of small raindrops in 1.0–1.4 mm diameters while throughfall drops exceeding 3.31 mm comprised 63.8% of the total drop volume. Similarly, the study of Li et al. (2019) revealed that throughfall drops were larger in size and that their DSD was enlarged with a mean volume ratio of large drops of 0.58 which was

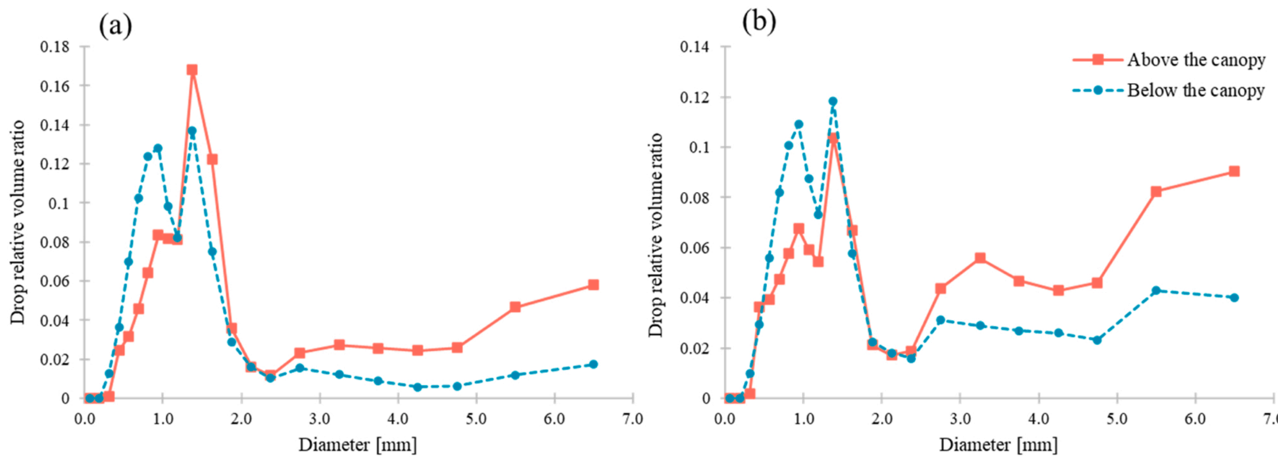

Fig. 4. DSD of open rainfall and throughfall during (a) leafed and (b) leafless periods.

more than twice higher than the 0.26 of open rainfall. Nonetheless, the DSDs in Fig. 4 demonstrated that there is a loss in the volume of drops under the birch tree which demonstrates the influence of the canopy in intercepting parts of the rainfall and splitting larger drops into smaller drop sizes. We hypothesized that this observation may imply important information, wherein the splitting of raindrops by the canopy over-compensates the coalescence of smaller drops and the genesis of drops which should be explored and verified in further studies.

Furthermore, D_{50} is also widely used as an index to understand the composition of DSD (Levia et al., 2019; Lüpke et al., 2019; Nanko et al., 2016), the value at which 50% of drops have a larger diameter and 50% are less (Meshesha et al., 2019). Across all rainfall events, the average D_{50} of open rainfall was 1.44 mm, ranging from 0.67 to 4.25 mm during the observation period. Whereas, throughfall D50 was between 0.86 and 2.24 mm with an average of 1.06 mm, representing a 26.6% decrease from what was observed above the canopy. It is corroborated by the result of Kruskal-Wallis H test indicating that a statistically significant difference exists between the D_{50} of open rainfall and throughfall ($p < 0.001$), which implies the influence of birch tree canopy in this particular DSD metric. Besides, our data showed that the D_{50} above and below the canopy was larger during the leafed period in comparison to the leafless period (Fig. 5b), but the Kruskal-Wallis H test revealed that the D_{50} does not significantly differ between phenoseasons ($p > 0.05$). The birch canopy reduced the D_{50} of rainfall both during the leafed (by 27.1%) and leafless period (by 25.9%). The study of Nanko et al. (2016) revealed that the presence or absence of foliage was among the most influential variables controlling the DSD of throughfall below the yellow poplar tree (*Liriodendron tulipifera* L.). On the other hand, our data found a good fit in the linear relationship between the event rainfall intensity and D_{50} (R2 = 0.51, $p < 0.001$), suggesting that the sub-canopy D_{50} increases with increasing rainfall intensity. The mean throughfall D_{50} under the birch tree was on average smaller than those reported in other DSD studies for deciduous trees. For instance, Lüpke et al. (2019) found that the throughfall D_{50} of a European beech was around 2.70 mm and Nanko et al. (2006) reported a range of throughfall D_{50} between 1.88 and 3.60 mm for a sawtooth oak tree.

Fig. 6 presents the density of drop numbers detected by Parsivel disdrometers for open rainfall and throughfall as a function of drop diameter and fall velocity (D-V). Also shown as a reference (red solid line) is the expected terminal fall velocity of raindrops per diameter, derived using the equation of Atlas et al. (1973). In general, the relationship between the observed drop diameter and fall velocity fairly agrees with the theoretical D-V model of Atlas et al. (1973). Thus, it is important to point out that the disdrometer-measured drop velocities of open rainfall and throughfall tend to be higher than the corresponding terminal velocities of Atlas et al. (1973), particularly in a family of small drops (<1 mm). But for drop diameters between 1 and 3 mm, we can see that the Atlas et al. (1973) equation provided a good fit to our D-V relationship.

Apparently, compared to open rainfall (Fig. 6a), throughfall has a

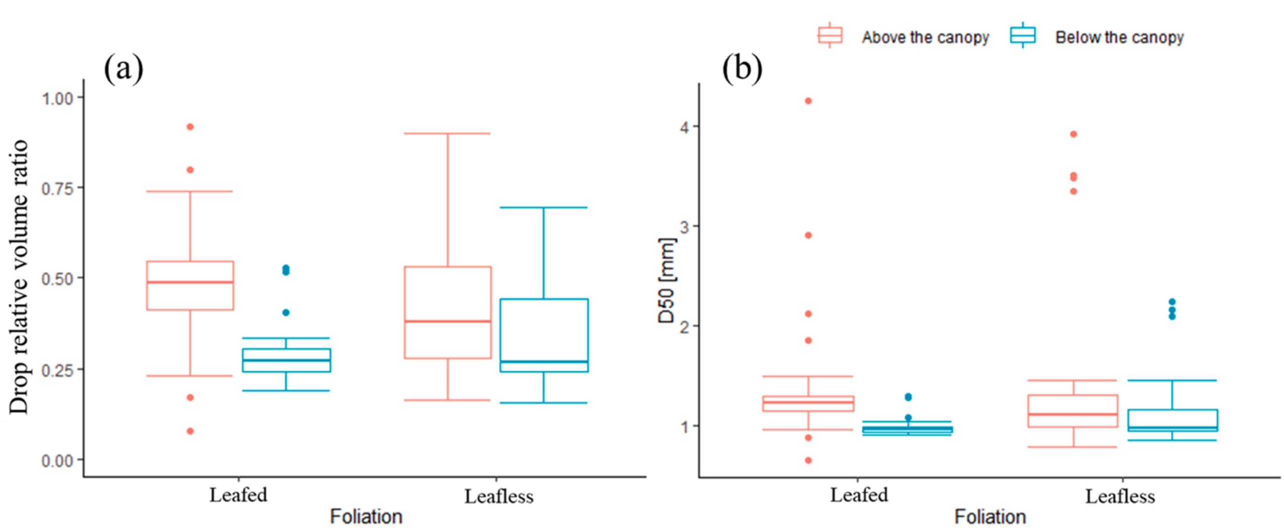

Fig. 5. (a) Boxplots of the drop relative volume ratio (>1.5 mm) and (b) the D_{50} above and below the canopy in leafed and leafless periods.

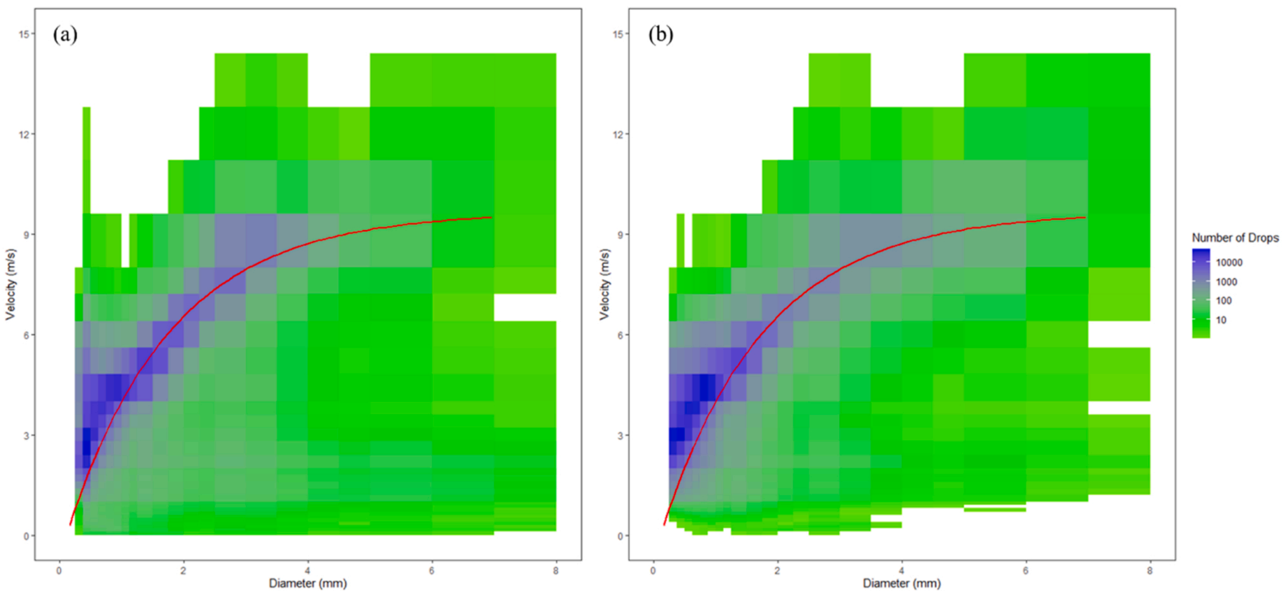

Fig. 6. Relationship between the diameter and velocity (D-V) of drops for (a) open rainfall and (b) throughfall. Identical color scales for both panels indicate the sum of drop counts inside each diameter and velocity class from observed 63 rainfall events. The solid red lines in each plot represent the terminal fall velocity curve based on Atlas et al. (1973) equation which was formulated from the laboratory measurements of Gunn and Kinzer (1949): $V_{terminal} = (9.65 - 10.3)e^{-0.6D}$.

higher concentration of drop particles < 1 mm with fall velocities ranging 2–5 m/s (Fig. 6b), which are close to the terminal velocity. As Levia et al. (2019) described, these throughfall drops are composed of splash droplets from the canopy that only require a short fall height to reach terminal velocity (de Moraes Frasson and Krajewski, 2011; Nanko et al., 2008), which can happen under the investigated birch tree canopy because the distance between the lowest branches and the ground is around 2.8 m. We can additionally distinguish from the spectrum of open rainfall that there is a considerable number of larger sized drop particles between 2 and 5 mm, which are characterized by velocities slower than expected of a drop falling in an open field condition. In particular, raindrops with a diameter of > 3 mm require a fall height of at least 12 m to gain its terminal velocity (Wang and Pruppacher, 1977).

The mean drop velocity of open rainfall measured by the disdrometers was 3.9 m/s, ranging from 3.1 to 5.0 m/s per event. The average velocity of throughfall drops was 3.7 m/s (3.4–4.1 m/s per event), which is 5% lower compared to that of open rainfall. It is expected that the fall velocities of throughfall drops were on average slower than open rainfall due to the influence of the canopy causing differences in the falling distance of drops. Other studies have also reported a decrease in the mean drop velocities of throughfall such as 7% under the open-grown birch tree (*Betula pendula Roth.*) canopy in Ljubljana, Slovenia (Zore et al., 2022) and 9% under the Scots pine (*Pinus sylvestris* L.) stand of Can Vila catchment in Spain (Pinos et al., 2020). Hence, the interactions of drop particles with the birch canopy have modified the physical characteristics of open rainfall, which are important determining factors that influence the kinetic energy of raindrops and their potential to cause soil detachment and/or soil loss.

The kinetic energy of raindrops plays an important role in the initiation of soil erosion (Li et al., 2019) thus, reducing this parameter is essentially significant in controlling the occurrence of soil erosion. TKE is a widely used indicator to express the erosive potential of rainfall below the canopies of any vegetation (Liu et al. 2018a,2018b) and it is strongly correlated with OKE. The kinetic energies of open rainfall

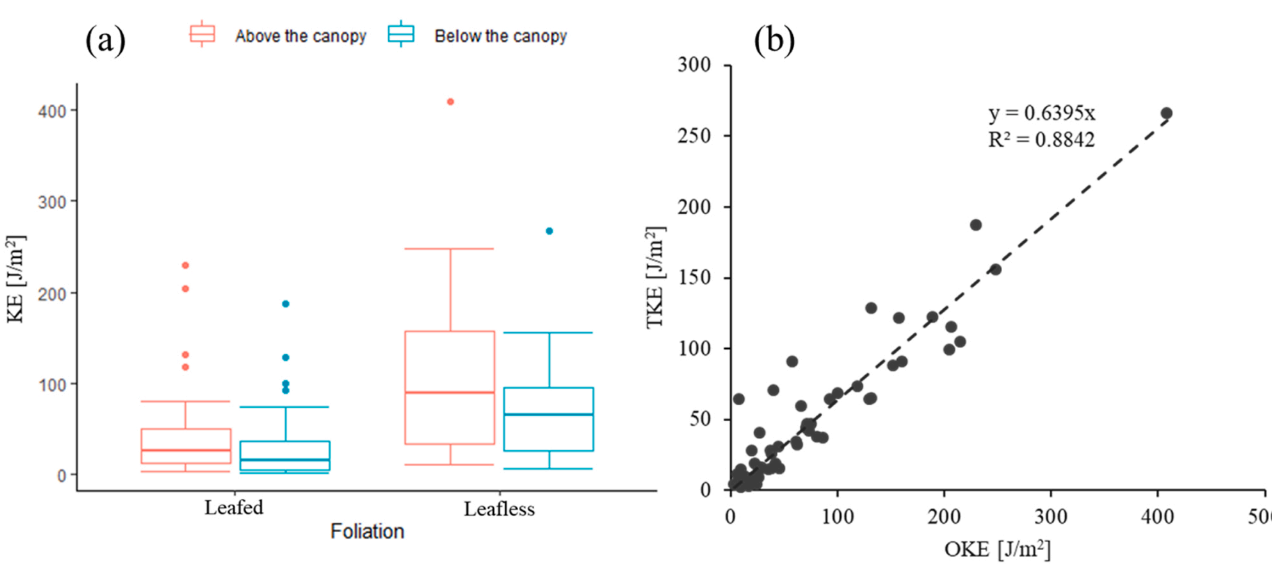

Fig. 7. (a) Boxplots of the kinetic energies above and below the canopy in leafed and leafless periods, (b) relationship of OKE and TKE.

(OKE) and throughfall (TKE) among 63 rainfall events vary from 3.24 to 408.29 J/m^2 (68.76 ± 76.61) and 2.89 to 266.91 J/m^2 (45.61 ± 50.48), respectively (Fig. 7). This is slightly lower than the values obtained by Zore et al. (2022) over a 14-month of observation for the same tree and location. Nevertheless, the Kruskal-Wallis H test result showed that the presence of birch tree elicits a statistically significant change in the kinetic energy of open rainfall ($p < 0.05$), thus reducing the mean OKE by 33.7%. Similarly, the splash cup experiment of Geißler et al. (2012a, 2012b) revealed an overall reduction of 59% in the kinetic energy of rainfall under the canopy of the studied tree saplings. Ma (2012) also observed that the corn canopy dampened the rainfall kinetic energy by 65–71% and the soybean canopy by 72–75%. In the following study, Ma et al. (2015) reported that the splash detachment rates under the two aforementioned crop canopies were lower than those on bare lands with a decrease of 62.3% and 61.8% for corn and soybean canopies, respectively. They associate this difference in the amount of reduction with the height of the canopy as corn has greater falling height, its effect on attenuating the energy is weaker compared to the soybean canopy (Ma et al., 2015).

Conversely, substantial studies have reported that TKE is higher below some tree canopies compared to OKE. For example, Nanko et al. (2004) found that the TKE beneath the mature Japanese cypress (*Chamaecyparis obtuse*) was more than twice higher than what was observed in the open. Under the rubber plantation, the TKE was found to be 1.84–2.32 times higher than OKE which greatly depends on the leaf area index (Liu et al. 2018a,2018b). While according to Zhou et al. (2002), the single-layer eucalyptus plantation has a significant effect on the reduction of rainfall kinetic energy when the rainfall amount is less than 5 mm or intensities are higher than 40 mm/hr, otherwise, the impact is reversed and consequently, accelerated the soil erosion process. The findings from the experimental measurements of Li et al. (2019) also discovered that TKE is higher when the rainfall intensity is less than 14 mm/hr and that this was reversed when the intensity is greater than 14 mm/hr because larger drops fail to reach their terminal velocities. These contrasting findings from diverse studies provide a reference regarding the differences in species-specific effects on TKE and the role of weather conditions.

However, our results are in contrast to some studies which showed that the D_{50} (e.g., Chapman, 1948; Brandt, 1989; Nanko et al., 2004) and kinetic energy (e.g., Chapman, 1948; Geißler et al., 2013; Li et al., 2019; Nanko et al., 2004) of throughfall is higher than that outside the canopy. The reasons for this observation could be attributed to the interception by the canopy, smaller leaf surface area of birch tree, and throughfall DSD. The drops falling from the upper layer of the canopy may have been re-intercepted and split by the lower parts of the canopy which overcompensates the formation of larger throughfall drops from the confluence of small drops. This mechanism may have affected the DSD of throughfall and therefore, resulted in the reduction of TKE as explained by Geißler et al. (2013). Also, it is important to reiterate that only one below-canopy disdrometer in a stationary position was used in the throughfall drop measurement during the entire study period such that the inherent spatial variability of throughfall under the canopy (Levia and Frost, 2006; Zabret, and Šraj, 2018) was not considered and there is a limitation of canopy cover variation. In this case, the obtained results may represent only the specific point under the canopy from where the disdrometer was installed, which was also mentioned by Lüpke et al. (2019) in their study. In addition to this, it is of particular interest to mention that TKE is affected in manifold ways by various biotic (e.g., crown base height, leaf area index, crown openness, etc.) and abiotic factors (e.g., rainfall characteristics, meteorological parameters, etc.) as a result of the changes in raindrop size distribution and velocity (Goebes et al., 2015b; Goebes et al., 2016; Levia et al., 2017). For instance, Zhou et al. (2002) showed that the ratio of TKE under the eucalyptus tree to OKE is greater than 1 for canopy heights of taller than 7 m and less than 1 for canopy heights smaller than 5 m. They added that the ratio changes dramatically when the height of the canopy is between 2 and 7 m. The investigations of Geißler et al. (2013) revealed that crown openness has a direct effect on TKE in which a reduction in TKE was observed in canopies with higher leaf area index (LAI). This is because rainfall interception is enhanced at greater LAI which decreases the amount of throughfall (Beidokhti and Moore, 2021) and negatively affects TKE. The same findings were reported by Liu et al. (2018a, 2018b) with regard to the effect of LAI on TKE and added that a rubber-based agroforestry system with low sub-canopy height reduces the erosive potential of throughfall as high canopies permit large throughfall drops to reach their terminal velocity. As explained by Goebes et al. (2015a), higher falling heights can increase the drop velocity of throughfall which contributes to higher TKE. This suggests that the role of multiple-layered canopies or sub-canopy vegetations play an important role in diminishing the kinetic energy of throughfall from the upper canopies (Liu et al. 2018a,2018b; Zhou et al., 2002).

In addition, Goebes et al. (2015b) highlighted that the species-specific effects on TKE were also mediated by leaf area and crown base height aside from LAI, tree height, crown area, and other canopy architectural traits. They found that the leaf area induced the most significant changes in species-specific TKE. The species of *Choerospondias axillaris* (35,484 mm^2) and *Sapindus saponaria* (42,231 mm^2) have the highest leaf areas among the investigated trees and the corresponding TKE beneath their canopies were significantly higher than the mean TKE of all species. Whereas, *Schima superba* and *Cyclobalanopsis glauca* with a leaf area of 3230 and 2474 mm^2, respectively have the lowest TKE. According to the rule-based analysis of Goebes et al. (2016), leaf areas exceeding 35,000 mm^2 led to high TKE while leaf areas below 6700 mm^2 produced low TKE. A higher leaf area provides a greater surface for the formation of larger drops from the coalescence of rainwater, resulting in higher TKE (Herwitz, 1987). However, it has been known from a large number of studies that the surface area of the leaves is one of the significant factors determining the amounts of interception with higher leaf area equates to greater interception rates, thus, decreasing the throughfall amount (Gómez et al., 2001; Kang et al., 2004; Muzylo et al., 2012). While the crown base height indirectly (as it is related to tree height) determines the falling height and fall velocity of throughfall (i.e., canopy drips) because the base of the live crown represents the last barrier in releasing throughfall drops (Goebes et al., 2015b). The height-drop velocity relationship from the experiment of Moss and Green (1987) showed that the erosive power of large water drops from the canopy increased rapidly over the first 2 m of free fall and drops falling to a height less than 0.3 m had small to negligible erosion. However, the experiments performed by some researchers pointed out that the height of the tree determines the species-specific differences in TKE (Foot and Morgan, 2005; Goebes et al., 2015b; Geißler et al., 2013) and is more influential in increasing TKE than the crown base height (Goebes et al., 2015b). In addition to these significant impacts of tree traits on TKE, the species comparison by Goebes et al. (2015b) revealed that the amount of throughfall and transformation of drop sizes and velocities also influence TKE and that higher throughfall amount does not necessarily equate to higher TKE. We can observe from the results of earlier studies mentioned above that TKE is a function of many biotic factors, specifically the plant's leaf and architectural traits in which large species-specific differences were observed.

Moreover, the TKE during the leafed period significantly differs from the TKE in leafless period ($p < 0.05$), indicating that TKE was also positively affected by the phenological condition of the canopy. The leafless state of the birch tree produced a TKE that is more than two times as high as the leafed state, mainly because of the absence of leaves in the canopy which is also associated with higher throughfall amount, higher drop number, and higher mode of drops > 1.5 mm. Additionally, our data shows that TKE significantly increases via linear correlation with increasing open rainfall ($R^2 = 0.80$, $p < 0.001$), and event rainfall intensity ($R^2 = 0.85$, $p < 0.001$) which indicates that rainfall characteristics govern the magnitude of raindrop energies as also described by Geißler et al. (2013). Though there is no general consensus about the relationship of TKE with throughfall amount (Liu et al. 2018a,2018b), we found a significant positive linear dependence between the two variables ($R^2 = 0.83$, $p < 0.001$, Fig. 6b). These results agree with the findings of earlier studies (i.e., Geißler et al., 2013, Goebes et al., 2015b; Liu et al. 2018a,2018b, Nanko et al., 2011).

The clustered heatmap (Fig. 8) is used to visualize the representation of the standardized data where each row is an observed rainfall event and the column is the corresponding entity's value on each measured variable. The hierarchical clustering analysis of rainfall events produced three main clusters which were described by 11 variables (OKE, TKE, D_{50} and relative volume ratio of drops > 1.5 mm of open rainfall and throughfall, Temp, R_h, W_S, W_d, W_G, VPD, and the number of drops). The first class, with the greatest number of events, is mostly characterized by smaller D_{50}, lower drop relative volume ratio, and lower KE which also describes the characteristics of the second class. Also, the two classes consist of events occurring in the leafed period of the birch tree which confirms the role of foliage presence as also illustrated in Figs. 5b and 7a. However, they differ in terms of their meteorological variables where the first class varies from medium-low to medium-high range of values while the second class has higher values of Temp, W_s, W_d, W_g, and VPD, except for the Rh which is considerably low. On the other hand, the third class clearly gives higher values of D_{50}, drop relative volume ratio, and KE which is associated with lower Temp and VPD and medium-high R_h, W_s, W_d, and W_g. Hence, we can observe that the number of drops (ND) in this class is noticeably greater compared to the previous classes because majority of the rainfall events clustered in this class are of moderate to heavy magnitude occurring during the leafless period. The utility of clustered heatmap visualization highlights the differences in the interaction of the considered variables in every rainfall event.

In order to gain insights into the associations of the 11 variables across all rainfall events, we performed a correlation coefficient analysis on the datasets. The analyzed variables are related to each other in different ways as shown graphically in Fig. 9 but we are particularly interested in the relationship between KE and meteorological variables. Among the meteorological variables considered, vapor pressure deficit (Spearman $\rho = -0.71$, $p < 0.001$) and air temperature (Spearman $\rho = -0.56$, $p < 0.001$) show a statistically significant negative correlation with OKE while relative humidity exhibits a positive correlation (Spearman $\rho = 0.66$, $p < 0.001$). However, the associations of these variables diminished when it comes to the kinetic energy of throughfall (TKE) which can be attributed to the influence of trees. These relationships can be substantiated by observing the associations of the variables on a rainfall event basis in Fig. 8. We can observe that in most rainfall events occurring in a weather condition with lower air temperature and

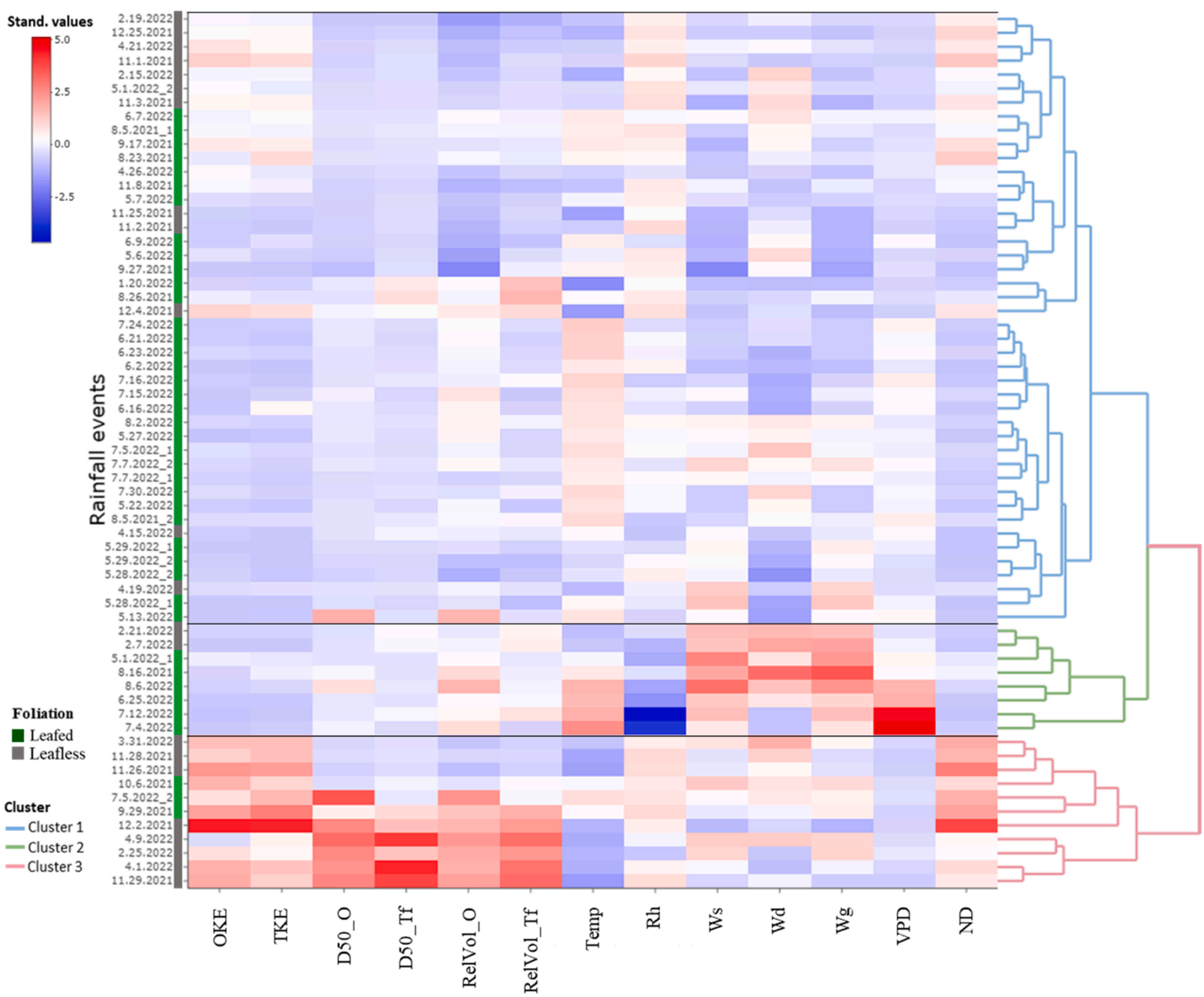

Fig. 8. Heatmap visualization of hierarchical clustering using the representation of the standardized values of considered variables across 63 rainfall events. The dendrogram of the events on the left was created based on the Euclidean distance and Ward clustering method. Color gradient indicates the intensity associated with standardized values with red as high (above the mean), white as 0 (reference), and blue as low (below the mean). Plot generated using the 'pheatmap' package in R (Kolde, 2019).

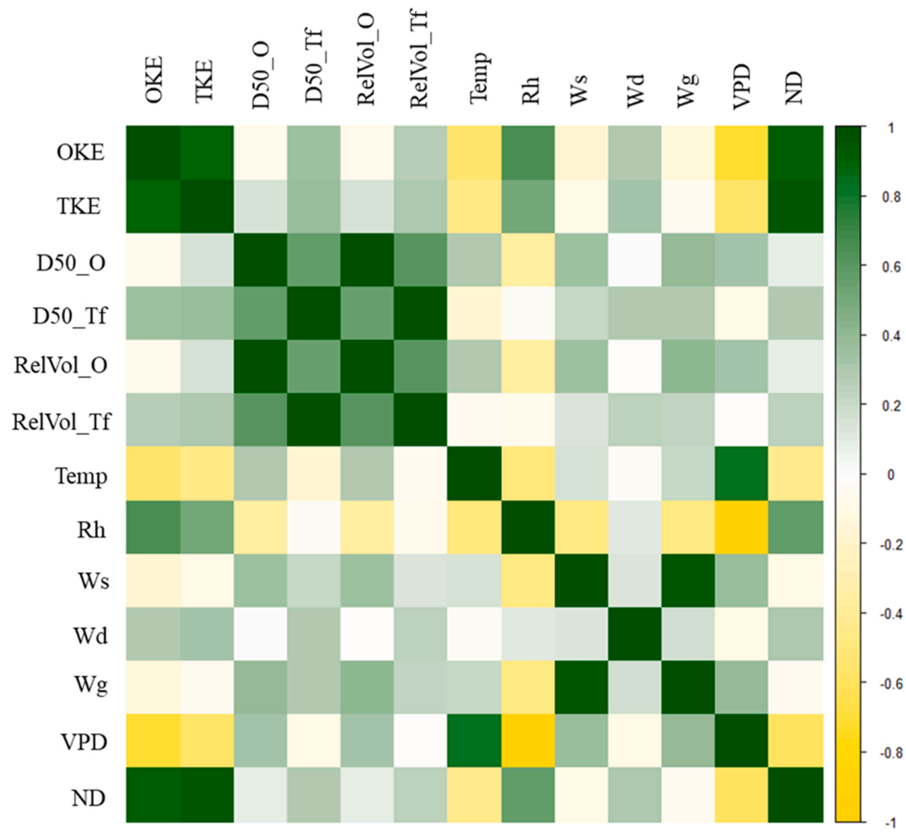

Fig. 9. Correlogram plot showing the association of variables used in the analysis based on Spearman correlation coefficient which is represented by the intensity of yellow and green color as indicated on the color gradient. Plot generated using the 'corrplot' package in R (Wei and Simko, 2021).

vapor pressure deficit, the kinetic energies of open rainfall and throughfall are generally high, including their respective D_{50}. However, the D_{50} and drop relative volume ratio have a weak correlation but are statistically significant with these three meteorological variables. In contrast, Nanko et al. (2016) found that air temperature and vapor pressure deficit are among the important meteorological factors influencing the drop sizes of throughfall which determines the erosion potential of raindrops. Accordingly, such weather conditions favor the formation of larger canopy drip, which has higher drop kinetic energies, and these are caused by higher surface tension and higher viscosity of the intercepted water (Levia et al., 2017; Nanko et al., 2016). But this formation of larger drops depends on the area, pinnation, and shape of the individual leaf (Goebes et al., 2015b). Also, such conditions are generally observed during the leafless states of the canopy when only the tree skeletons (branches, twigs, etc.) play the function of intercepting the rainfall. Additionally, during this colder season together with higher relative humidity, a temperature inversion is a regular phenomenon in the city of Ljubljana due to its location inside the basin, and this causes fog to hang heavy and low over the city (Kikaj et al., 2019; Rakovec et al., 2002). Though not explored in the present study, fog seems to have a role in the canopy drip generation process (Levia et al., 2017) because deposit fog droplets coalesce on foliar and woody surfaces (Holder, 2004) and in the event of rainfall, these will contribute to the genesis of larger canopy drips. On the other hand, warmer temperature facilitates faster evaporation rates for the intercepted water, which allows the canopy to have extra storage capacity for the incoming rainfall. Hence, the explanation behind this finding boils down to the seasonal changes in canopy phenology and variability of rainfall with high-intensity rainfall mostly occurring in warmer months with full-leaf canopies. As mentioned by Levia and Herwitz (2000), foliation cannot be investigated independently from other seasonal variables (e.g., temperature) which affect the evaporation, viscosity, and surface tension of water.

Wind speed, wind direction, and maximum wind gust were found to have no distinct strong correlation with KE, D_{50}, and drop relative volume ratio which may indicate the complexity of the influence of wind characteristics on the relevant processes under the canopy. Nevertheless, we can see from Fig. 8 that rainfall events associated with higher wind speed and maximum wind gust have smaller D_{50} and lower drop kinetic energies. Though most studies evaluating the effect of meteorological conditions are directed towards throughfall DSD and not enough research is conducted with regards to TKE, the close relationship between throughfall generation and TKE (Senn et al., 2020) can be used as a basis. Thus, this does not necessarily mean that what influence the DSD of throughfall will also influence TKE. Another finding from the study by Tilg et al. (2020) implies a decrease in the kinetic energy of rainfall with increasing wind speed because such condition modifies the shape of the DSD by breaking up larger drops into smaller droplets (Testik and Pei, 2017). Nanko et al. (2006) also observed smaller throughfall drops under coniferous and deciduous trees in conditions with severe canopy vibration due to the high wind speed which dislodges the intercepted water thus, reducing the coalescence of raindrops in the leaves. Meanwhile, Nanko et al. (2016) found that wind direction and maximum wind gust speed did not exert a significant effect on the drop size of throughfall beneath a yellow poplar while air temperature and vapor pressure deficit appeared to be effective meteorological factors.

4. Conclusions

This study demonstrates the characteristics of throughfall drop size distribution (DSD) and throughfall kinetic energy (TKE) below the birch tree canopy using an optical disdrometer. Simultaneous monitoring of open rainfall and throughfall reveals that the deciduous character of the birch tree modifies the amount, total drop number and volume, D_{50}, drop fall velocity, and kinetic energy of rainfall reaching the ground. The results show that throughfall has a lower number of drops, slower drop velocities, and smaller D_{50} which primarily consists of smaller drop diameters compared to those of open rainfall. Also, throughfall DSD, $D_{50,}$ and KE vary considerably at different phenological conditions of the birch tree canopy. The presence of foliage caused the total number of throughfall drops to be higher than the open rainfall while in the absence of foliage, the effect is the opposite. Overall, throughfall drops comprise primarily (89–90%) of drops below 1 mm, indicating that the physical presence of the canopy breaks the larger drops into smaller droplets. This shift in the DSD of throughfall to less (by number and volume) and smaller drops caused the corresponding D_{50} to be, on average, 1.4 times smaller than that of open rainfall. Similarly, the birch canopy also weakens the erosive power of raindrops as it strikes the soil surface. Mean TKE is 33.7% lower than the OKE and its greatest effect in reducing the KE of rainfall was observed during the leafed period of the birch canopy with TKE being more than 50% lower than in the leafless period. Furthermore, the results of the non-parametric correlation tests reveal that vapor pressure deficit, air temperature, and relative humidity are significantly associated with the kinetic energies of throughfall below the birch tree canopy. Correlations indicate that TKE increases during events occurring in colder conditions with low vapor pressure, high relative humidity, and in the absence of foliage. It thus appears that the canopy phenological conditions of birch tree induced more influence on TKE than the meteorological conditions which are associated with seasonal variation. However, further research is needed to examine this influence in a forest environment with different growing and climate conditions and how the degree of influence varies with the density of such tree species. It is also imperative to install more disdrometers below the canopy for throughfall drop measurement to reduce the effect of spatial variability and to include the variation of canopy cover in a tree. Our results accentuate the importance of understanding the different characteristics of throughfall below the birch tree canopy and the effect of meteorological conditions which is necessary for the prediction of soil erosion processes in areas where this tree species is abundant in nature. It supports the idea that some tree species can function as erosion inhibitors and underscores the necessity of an optimized selection of tree species for afforestation programs, particularly in areas prone to rainfall-induced soil erosion.

CRediT authorship contribution statement

All authors contributed to the conceptualization and design of the study. **Mark Bryan Alivio:** Formal analysis, Visualization, Writing – original draft. **Nejc Bezak:** Writing – review & editing, Supervision, Validation. **Matjaž Mikoš:** Writing – review & editing, Supervision. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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