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Practical Performance and User Experience of Novel DUAL-Flush Vacuum Toilets

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Abstract: Vacuum toilets have gained increasing attention in circular urban development projects, because of their marked water saving qualities compared to conventional flush toilets and the increased resource recovery potential for energy in the form of biogas and phosphorous as, e.g., struvite from the resulting concentrated wastewater. A further reduction of the flushing volume of vacuum toilets would also bring nitrogen recovery options in reach. In the framework of the EU Horizon 2020 project Run4Life, a novel dual-flush vacuum toilet was developed and tested at two sites and combined with an analysis of the flushing patterns and a qualitative user survey. The results show that a 25–50% lower flushing water consumption and accordingly 1.5–2 times higher nutrient concentrations are achievable with this novel type of vacuum toilet. The usage frequency of the dual flush feature was higher in residential homes than in an office building, which also had urinals installed at the men toilets. A notable fraction of toilet visits in which the toilet was flushed twice as well as user feedback on dissatisfactory cleaning effects suggest that the applied reduction in water use is most likely the upper limit of what can be achieved in this type of toilet.

Keywords: dual-flush toilets; vacuum toilets; water saving; resource recovery; blackwater

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1. Introduction

Vacuum toilets, mainly applied on ships, trains and airplanes, are gaining increased attention in green urban development projects due to their low flushing water consumption. The first installations are more than 20 years old, but, until recently, larger vacuum toilet installations in urban buildings have mainly be selected for the purpose of water saving in urban regions with water scarcity. Typically, a vacuum toilet is flushed with 0.8–1.5 L, resulting in a notable water saving effect compared to ordinary gravity toilets that have a flushing volume in the range of 3–9 L per flush [1]. The wastewater fraction from the toilet, called blackwater, contributes to 60–70% of organic matter and 70–90% of the phosphorous and nitrogen mass load a household discharges via sewerage [2]. This makes it attractive to separate blackwater at source for recovering nutrients and organic matter. With vacuum toilets, blackwater of a higher concentration is achieved, increasing the efficiency of the resource recovery processes [3,4]. Some of these processes are well developed and widely applied, such as UASB for energy recovery from organic matter or struvite precipitation, in which phosphorous can efficiently be recovered. For nitrogen, on the other hand, only limited, small-scale and not very cost-efficient recovery processes are available with the present type of blackwater from vacuum toilets. More efficient recovery methods for nitrogen (e.g., developed for separated urine), would require a concentration level that is notably beyond the capability of existing vacuum toilets.

For this purpose, a novel type of vacuum toilet was developed within the European research project (H2020) *Run4Life* with the goal to halve the flushing water consumption

compared to existing vacuum toilet models. Run4Life, short for "Recovery and Utilization of Nutrients 4 Low Impact Fertilizer", proposes a radical new concept for wastewater treatment and nutrient recovery, based on source-separated collection of domestic wastewater and kitchen waste. One key component of this concept is a toilet with an extremely low flushing volume, which produces blackwater of a high concentration with high resource recovery potential. This was achieved by implementing saving flush mode for urination. The latter, generally referred to as a dual-flush feature, has become a common feature of modern gravity toilets [5]. These novel dual-flush vacuum (*DualFlushVac*) toilets developed within *Run4Life* are operating at flushing volumes of 0.7 L for the regular flush and 0.4 L for the water-saving flush mode, giving an average flushing volume in the range of 0.5–0.6 L. Compared to existing vacuum toilet models, which have a typical flushing volume of 0.8–1 L within small installations, such as trains, cottages or mountain lodges [6] and 1.2–1.5 L within larger vacuum sewer systems on ships or urban buildings [2], an additional water saving rate of up to 60% may be achieved with *DualFlushVac* toilets. However, the water saving effect of the dual-flush feature is highly dependent on the user's needs and awareness. The more frequently a water-saving flush is applied the lower the average flushing volume and the higher the concentration of the blackwater. Regardless of its widespread implementation in modern gravity toilets, little work has been done to date to investigate the usage frequency of a water saving flush feature [5,7]. Moreover, there is only limited information about the user acceptance of these types of toilets [8]. One further important question is whether insufficient cleaning effects of the flush may result in a need for flushing the toilet twice, so-called double flushing, which would result in a doubled flushing volume and outweigh the water saving effect of a *DualFlushVac* toilet compared to existing vacuum toilets. No studies that have investigated this double flushing issue in detail were found among the existing literature.

To address these questions, this study has gathered data at two pilot installations: one in an office building and one in residential houses. The results encompass quantitative data on the frequency of double flushing as well as the water-saving flush usage with qualitative user feedbacks.

2. Methods

The newly developed *DualFlushVac* toilets have been installed at two locations: an office building and a residential housing area. Both sites are located in Sneek, NL, within approximately one kilometer of each other. There is no ownership relationship between the residential housing area and the company located in the office building and there were no employees living in any of the residential houses at the time of the study. Hence, despite its geographical closeness, the two groups of toilet users represent independent populations.

2.1. Dual-Flush Vacuum Toilets

The *DualFlushVac* toilets used for this project represent a special configuration of a recent soft-sound vacuum toilet model (Jade^{TM}, Jets Group, Hareid, Norway). Nominal sound levels given by the manufacture are 71 dB $L_{p,A,T}$ and 83 dB $L_{p,AF,max}$. (determined according to ISO 3747:2020). As is usual for vacuum toilets, flushing of the toilet model is pneumatically driven via a pressure button in its standard configuration. The *DualFlushVac* configuration, on the other hand, is flushed by an electronic microcontroller which is mounted behind the flushing buttons. The microcontroller features a further two-wire Modbus communication port for remote parametrizing and monitoring. Flushing of the *DualFlushVac* toilet starts with a phase in which the toilet bowl is cleaned with fresh water sprayed out via nozzles and excrement and dirty water are sucked into the vacuum sewer line. Thereafter, the toilet bowl is refilled with fresh water, so that the next user has a visibly clean water table in the toilet bowl (more details can be find in [9]). To avoid multiple activation of the flushing sequence and, consequently, the release of flushing water before an ongoing flush is accomplished, both buttons are blocked during the whole flushing sequence. Hence, any potential flushing button activations within the timeframe of an

active flushing sequence will not trigger or log a new flush. This is also in accordance with other studies that were logging flushing activities [10]. The water pressure in the line may vary depending on the floor where toilets are installed and the distance to the freshwater main, which, again, may impact the flushing efficiency and consumption of fresh water. To ensure as equal conditions as possible between the different toilets, with a flushing volume of 0.7 ± 0.1 L and 0.4 ± 0.1 L for the normal and saving flush, respectively, the opening time of the freshwater valve was adjusted to the actual pressure conditions by using the visible water table at the end of the refill phase as an indicator [9].

2.2. Demo Site 1: Office Building

The office building facilitates eight toilets for each gender, distributed over three floors. 60–80 people work in the office building, with most of them (70–80%) male. Vacuum toilets were solely installed in the eight toilets for men. The vacuum is provided by a constant vacuum aggregate (Jets Group, Hareid, Norway) that starts when suction pressure falls below the critical level of 400 mBar and stops again when the setpoint of 500 mBar is reached. Six of the vacuum toilets have been retrofitted with *DualFlushVac* toilets equipped with two flushing buttons, while two toilets, one on the ground floor and one on the first floor have been retrofitted with a vacuum toilet of the same model but with only one flushing button. The single-flush toilet at the ground floor was parametrized with the saving flush mode and the single flush toilet at the first floor with the regular flush mode, corresponding to a flushing volume of 0.7 and 0.4 L, respectively. All of the eight retrofitted toilets (6 *DualFlushVac* toilets and 2 single-flush toilets) are connected to a PLC controller and operational parameters can be individually adjusted while flushing activity is logged. A pressure transmitter (3500 Series 0–4 bar relative, Gems Sensors & Controls, Plainville, USA) was installed in the flushing water supply line at the ground floor and at the third floor. The men's toilet rooms facilitate two to thre urinals in addition to the vacuum toilets on each floor. These urinals remained unchanged and were normally accessible throughout the whole study period. Log data are continuously transferred to a cloud-based SCADA server (Inductive Automation, Folsom, CA, USA). The use of the urinals and the women's toilets were not part of this study's scope.

2.3. Demo Site 2: Residential Houses

The demonstration site at the residential houses encompasses 32 row houses with an already existing vacuum sewer system with 64 toilets in total. The houses are owned by two real estate companies and rented out to the inhabitants. Most houses are inhabited by two to four persons. The exact number of inhabitants, as well as the gender distribution, is unknown, but is assumed to have little variation among the 32 houses. The houses have two floors with one toilet on each floor. In 29 of the 32 houses, the existing conventional vacuum toilets are retrofitted with new *DualFlushVac* toilets (two toilets in each house). At the remaining three houses, inhabitants did not want to retrofit their toilets. Thus, six of the 64 toilets remain as conventional vacuum toilets, with a flushing volume of 1.2–1.5 L. The sewer mains are made of large-dimension PVC pipes (DN90) that are over 100 m in length. The vacuum is provided by a central vacuum station (Roediger Acceptance Group, Hanau, Germany) with a suction pressure setpoint of 600 mBar. Due to Dutch privacy regulations, the residential house toilets cannot be connected to a central server or monitoring unit per default. Adjustments of parameters are completed using a handheld device in each house.

2.4. Data Acquisition and Processing

Regarding the office building, each toilet flush was registered with the flushing time, flushing type (normal or saving) of the current and previous flush, and the time passed since the last flush. Regarding the residential area, Dutch privacy regulations did not allow registration of the usage patterns of the installed toilets per default. However, five of the 28 households agreed that the flush activity of their toilets could be logged. In these houses, log data are transmitted to a cloud-based SCADA server (Inductive Automation, Folsom,

CA, USA) via a temporary installed GSM based communication device. In view of the privacy constraints, each toilet was attributed a random ID number providing information on which floor, but not in which house the toilet was located. Therefore, it was not possible to allocate the usage pattern of a toilet to a particular household. To avoid registration of diurnal usage patterns, flushes are registered with a random, rather than incrementing ID, and the day, but not the exact time a flush occurred, was registered. It is therefore not possible to allocate an exact order of the flushes that occurred at a particular toilet. For each flush, the day, flush type (normal or saving) of the current and previous flush, and time passed since last flush were registered. The type and time frame of previous flushes were pre-processed within the microcontroller in each toilet and submitted to the server at the beginning of a new flush.

Data were analyzed statistically on monthly basis. The significance was tested with help of an unpaired, two-tailed T-test with a threshold of $p = 0.05$. p-values below 0.01 are not displayed in more detail.

2.5. User Survey and Qualitative Feedbacks

In order to acquire feedback regarding the user's experience, qualitative data have been collected from the office building users with help of an online multiple-choice survey (Google Forms). For the office building, the survey was distributed via the mail to the employees of two companies that are located in these office facilities. For the residential area, the survey was distributed via the housing companies. The questionnaire encompassed, in total, six questions with four answer options for each question. Question one was related to the general experience with vacuum toilets, and questions two to four were related to usage of saving flush mode and satisfaction with the cleaning effect from flushing. Questions five and six dealt with the sound perception of the vacuum toilets (Table 1). Aside from the multiple-choice questions, survey participants were given a facultative option to provide open feedback via a text form. In addition, supplementary open qualitative feedback was gathered within individuals during spontaneous discussions with a couple of randomly selected toilet users. These discussions are not transcribed in detail, but the key outcomes have been recorded in the form of anonymized notes.

Table 1. Questions, answer options and summary of results of the multiple-choice survey performed at the residential area and office building about user perception on dual-flush vacuum toilets.

Question (Q#)/Answer Option	Residential % of Total 6 Responses	Office % of Total 39 Responses
Q1: What is your experience with the use of the new dual-flush vacuum toilets in general?		
I do not experience a difference in comparison with other (gravity) toilets elsewhere in the building	n.a *	38.5
They function properly, but I have a preference for ordinary gravity toilets	17	25.6
I prefer them over the vacuum toilet models that were previously installed in the building	50	28.2
I do not like the new dual flush vacuum toilets	33	7.7
Q2: How often do you use the water-saving flush button in the dual-flush vacuum toilets?		
Often	33	17.9
Never	0	28.2
Occasionally	33	35.9
I did not know such a button existed	33	15.4
Blank	0	2.6
Q3: Is the water-saving flush button working properly?		
In most cases	17	23.1
Not always	33	10.3
In most cases I have to flush twice	33	30.8
Never tried	17	35.9
Q4: When you arrive in the toilet, how often do you find a dirty toilet bowl (from a previous user) and do you flush the toilet twice (before and after use)?		
Never	0	17.9
Sometimes	17	48.7
Often	83	25.6
I always flush before I use the toilet	0	5.1
Blank	0	2.6
Q5: How often does flushing after using the toilet does not give the desired (clean) result?		
Rarely	0	20.5
Often (every second or third time that I make use of the dual-flush toilets)	17	46.2
In most cases when I make use of the dual-flush vacuum toilet	50	25.6
I always flush twice irrespective what type of toilet I am using	33	7.7
Q6: How do you experience the noise level that the toilet produces		
Less loud as compared to ordinary (gravity) toilets	17	0
Comparable to ordinary (gravity) toilets	17	23.1
Definitely louder than ordinary (gravity) toilet but is does not disturb me	17	66.7
Very disturbing	50	10.3

* This answer was not applicable for the residential area as there were no other toilets than dual-flush vacuum toilets installed in the building.

3. Results and Discussion

From the office building, in total 39 persons responded to the multiple-choice survey. This corresponds to 50–65% of the approximately 60–80 people that are working in the office facilities on a regular basis. For the residential area, unfortunately only one of the two housing companies was willing to forward the request to their tenants. From the total 13 households belonging to the collaborating company, six responded to the multiple-choice survey. These respondents represent 46% of the households belonging to that respective company and 20% of the total 29 households that have a *DualFlushVac* toilet installed in

their house. The limited feedback received from the inhabitants of the residential area was caused by the aforementioned lack of collaboration from one housing company and Covid-19 restrictions, which made it difficult to approach inhabitants in person. Therefore the results of the questionnaire can only be interpreted as simple qualitative indicators from a smaller group of inhabitants, which may not be representative for the whole population living in the 32 row houses. Since the multiple-choice survey was done anonymously, it is unknown from which households they exactly originated so that they cannot be directly linked to the five houses that voluntary participated the flush monitoring campaign. On the other hand, it can be assumed that at least some of these households also responded to the questionnaire.

In general, approximately half of the multiple-choice survey respondents expressed a neutral or positive perception about the new *DualFlushVac* toilets. Nevertheless, a notable fraction of respondents would prefer ordinary toilets or even stated that they do not like these new toilets (Table 1, Q1). The reasons for a negative perception might be related to noise emissions. Four out of the five respondents that are disliking the *DualFlushVac* toilets perceived its sound as more disturbing than that of gravity flush toilets. The fifth of those respondents, on the other hand, seems to dislike the *DualFlushVac* toilets mainly due to insufficient cleaning effects rather than the noise emissions that he/she perceived as comparable to gravity flush toilets.

Noise emissions seem to be a more critical issue in the residential area, where half of the respondents expressed experiencing the sound of the *DualFlushVac* toilets as very disturbing (Table 1, Q6). One reason for this difference may be the applied higher vacuum level of 400 mBar absolute pressure in the vacuum sewer of the residential area, compared to 500 mBar absolute pressure in the vacuum sewer of the office building. This higher absolute pressure results in a higher sucking velocity and, accordingly, greater sucking noise in the residences. High noise emissions are likely, in general, to be a more critical issue in private homes than in offices or other types of public buildings, especially during night-time.

At both pilot sites, a notable fraction of flushes occurred within a relatively short time frame after the previous flush at the same toilet. For time intervals shorter than one minute, and, to a lesser extent, also for time intervals ranging from one to two minutes, a notably higher frequency of flushes was registered compared to the time interval ranges lasting more than two minutes (Figure 1). It is therefore assumed that within some of the toilet visits, toilets are flushed twice (e.g., to deal with unsatisfactory cleaning of toilet bowl). This hypothesis regarding the occurrence of such so called double flushes is also supported by the multiple-choice feedbacks (Table 1 Q3–Q5). Based on the pattern given by Figure 1 and the open qualitative feedbacks from user discussions about the typical length of a toilet visit, a threshold value of 180 s was used to determine these so-called double flushes for further analysis and discussions. A minor fraction of double flushes are likely falsely declared with this approach, since intervals between toilet visits of different persons can also be shorter than three minutes. Especially in periods when people have a tendency to go to toilet (e.g., before leaving the house in the morning, going to bed or after lunch break in an office), waiting queues may occur in which toilet visitors are pushed to keep their session as short as possible. On the other hand, the user discussions at the same time indicate that some toilet visits for which double flushes likely occur last notably longer than 3 min. It is therefore assumed that using the threshold of 180 s provides a reasonably representative picture of the number of determined double flushes.

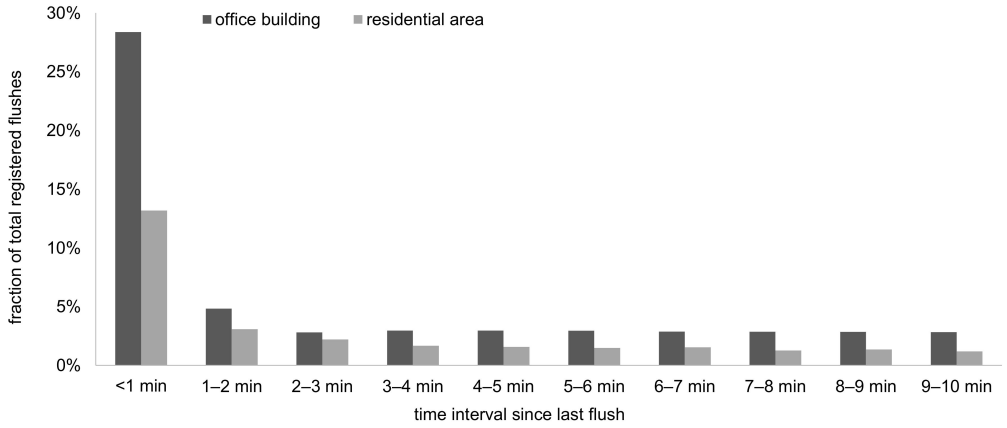

Figure 1. Fraction of total registered flushes for different ranges of time intervals to the last flush at the same toilet.

The total number of flushes per toilet that have been registered within the monitoring periods, lasting for thirty-five and nine months, varied from 1900 to 16,000 and 600 to 3600 for the office building and residential area, respectively (Figure 1). All installed toilets provided sufficient data and are included in the further statistical analysis. For the office building, a significant ($p < 0.01$) higher frequency of toilet usage was registered for the toilets located at the first floor, compared to the ground floor and second floor. At the residential homes, usage frequency shows more equal distribution between the two floors, with a slightly, but not significant ($p = 0.03$), higher usage of the ground floor toilet (Figure 2). The distribution of usage frequency in the office building reflects the distribution of working places over the three floors and is therefore in accordance with expectations. At the residential homes, the more frequent usage of the ground floor toilet is potentially related to its proximity to the living room in which inhabitants, when at home, are assumed to spend most of their time, except when sleeping. At both sites, a slightly lower tendency for water-saving flush usage could be observed at the uppermost floor (the second floor at the office building and the first floor of the residential area). This may be related to a lower pressure in the freshwater supply line and, accordingly, a poorer cleaning effect of the nozzle-based flushing. At the office building, supply pressure at the second floor was with 1980 $\pm$ 400 mBar significantly ($p < 0.01$) lower than the 2820 $\pm$ 350 mBar measured at the ground floor. Due to practical reasons, it was not possible to install pressure transmitters in the residential area. However, according to the plumbing company who installed the *DualFlushVac* toilets, pressure in the freshwater supply line is expected to be in the range of 2–2.5 bar in that area (Otte Installaties, personal communication, 15 October 2019). Considering a pressure loss of 0.25–0.3 bar that is expected with a floor height of 2.5 m, pressure conditions at the first floor of the residential houses are likely comparable to the third floor of the office building. Qualitative observations of the flushing sequence indicate that the cleaning efficiency of the flushing nozzle drops notably when the flushing water supply pressure falls below 2 bar, especially at short flushing times as when the saving flush is applied. Hence, experiences with insufficient cleaning may be a reason that people used the water-saving flush less frequently on the upper floors. Ensuring sufficient water supply pressure over all floors is therefore an important issue to consider when installing *DualFlushVac* toilets and other types of high water-saving vacuum toilets.

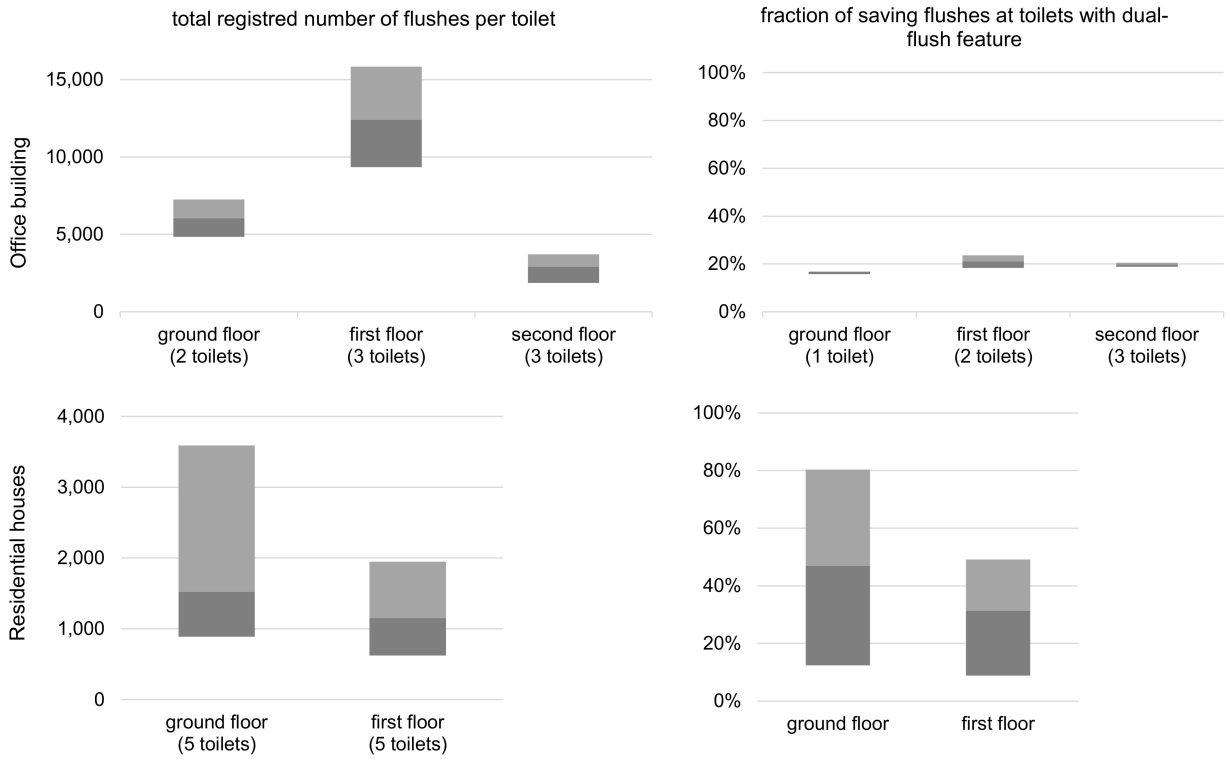

Figure 2. Left: Total number of registered flushes per toilet. The figures include also the two toilets at the office building with only one flushing button. Right: fraction of saving flushes at the toilets with two flushing buttons (dual-flush feature). The upper panels show the data from office building and the lower panel from the residential houses. The bars show the variation between the toilets using minimum, average and maximum for each floor.

The water-saving flush button was significantly ($p < 0.01$) used more frequently at the residential area than in the office building. This is in accordance with the results of the multiple-choice survey, in which only 46% of respondents from the office building stated that they are using the water-saving flush button occasionally or often, compared to 66% of respondents from the residential area. A notable fraction of respondents from the office building, accounting for 28%, has never used the saving flush button, despite being aware of its existence. In contrast, it seems that all respondents from the residential homes, knowing about the saving flush feature, have taken it into use. At both sites, a remarkable fraction of respondents was not aware of the existence of a water-saving flush feature (Table 1, Q2). This indicates that user information was likely insufficient, especially within the residential area where one third of the respondents claimed that they did not know about existence of a saving flush. Hence, user information on the saving flush feature, as well as general awareness on water saving, are important aspects that need to be considered when introducing dual-flush toilets of any type.

A possible explanation for the lower fraction of water-saving flushes at the office building may be that urinals are likely preferred by the male users for urination while the vacuum toilets are mainly used for defecation. This is in accordance with the findings on dual-flush urine separating gravity toilets installed in an office building beside urinals, where the saving flush usage varied around 10% for the male toilets [10]. Considering that the installation of urinals is common in office and public buildings, the data nevertheless provide a representative picture for the male population at such places. Hence, the data may imply that the achieved water saving effect with a saving flush feature is marginal for male toilet facilities that are equipped with urinals. Lacking incentives to save water may be a further reason for the low frequency of saving flush usage at the office building. In public locations, including office buildings, users do not have to pay for the water usage and there is rather no risk that other users will observe a potential ignorance of

the saving-flush feature [2]. Qualitative feedback gathered within this study indicate that this hypothesis may also apply for many private households. In contrast, the general pressure of social norms makes users worried that the next user may be dissatisfied with the cleanliness of the toilet bowl and attribute the dirt to the previous user [7]. Users may therefore simply choose the best option for their immediate need of leaving a clean toilet bowl, rather than considering the more long-term environmental need of water saving [5]. The survey responses of this study may support this hypothesis, as 36% of respondents stated that they are never using the saving flush button, even though they are aware of its existence (Table 1; Q2). However, considering the presence of urinals at each floor of the office building, some of the users may use the *DualFlushVac* toilets only for defecation and, accordingly, flush with the regular button. The hypothesis on the presence of a social pressure around leaving a clean toilet is further questioned by the fact that a notable number of the survey respondents stated that they often find the toilet in a dirty state from the previous user (Table 1; Q4).

Both pilot sites show a similar pattern with a distinct greater frequency of flushes occurring within three minutes or less up to the previous flush at somewhat different magnitudes. As outlined earlier, a potential reason for the observed pattern is likely to be that people are flushing twice within a single toilet visit. The high frequency of such double flushing may outweigh the benefits of an *DualFlushVac* toilet in terms of freshwater consumption and may enhance energy consumption due to a higher number of flushes and, accordingly, pumping cycles of the vacuum aggregates per toilet visit. A literature review performed within this study indicated that a potential negative impact of double flushing is also a known issue for water saving gravity flush toilets, as mentioned in a number of fact sheets and other types of non-scientific publications. However, no study could be found that investigates and quantifies the occurrence of double flushing and its impact on water saving on a scientific level. Therefore, double flushing needs closer attention.

A notable frequency of putative double flushing activity has been identified at the office building, accounting for up to 49% of flushes for some of the toilets during some periods, which is significantly ($p < 0.01$) higher than at the residential area. (Figure 3). These data are partly reflected by the multiple-choice responses, in which a majority of respondents at both sites indicated a frequent need for flushing the toilet twice, either due to a dirty bowl left by a previous user or insufficient cleaning after flushing (Table 1; Q4; Q5). In contrast to the log data, the multiple choice results point to a greater frequency of double flushing at the residential area than the office building (Table 1; Q5). The reason for this discrepancy may be due to the relatively small sample groups referring to only five households for the log data and six households that responded to the multiple choice survey. The households related to these two sample groups are not necessary the same, and might therefore have different perceptions and, accordingly, different usage patterns of the *DualFlushVac* toilets. Somewhat surprisingly, five out of six residential area respondents claimed that they often have to start a toilet visit with flushing in order to clean up residuals from the previous toilet user, which is notably higher than the 25% respondents from the office building who gave a similar answer (Table 1; Q4). Considering that a limited number of socially closely connected people use a toilet in a private household, a greater awareness of leaving a clean toilet for the next user would have been expected. For obtaining a deeper insight into this discrepancy, a more detailed overview over the people living in those households would be needed, which was unfortunately prohibited due to privacy concerns and regulations.

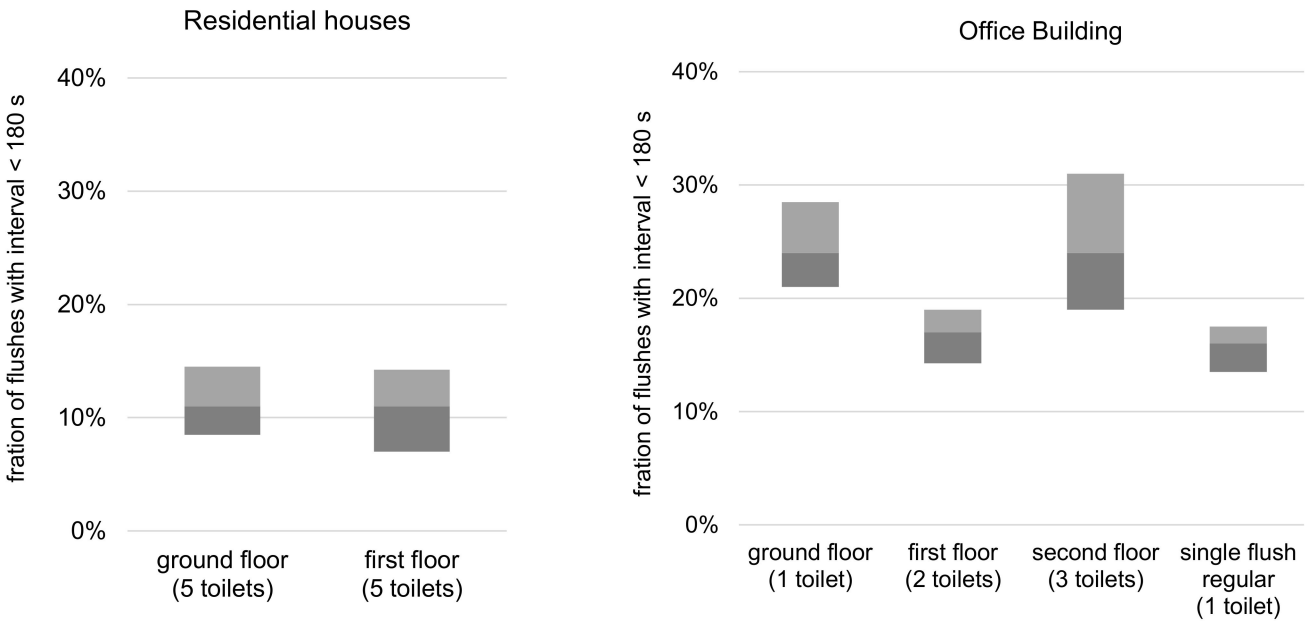

Figure 3. Fraction of flushes occurred upon 180 s to the previous flush at the same toilet identified as putative double flushes of office building including the two toilets with only one flushing button (single flush) and residential houses. The bars show the variation of the monthly average values per toilet, with the intervals between median and first and third quartile.

Comparing the two vacuum toilets that are providing only one flushing mode shows that the fraction of putative double flushes was significant lower ($p < 0.01$) at the first floor toilet parametrized with the regular flush mode and significant higher ($p < 0.01$) at the ground floor toilet parametrized with the water-saving flush mode (Figure 3). Hence, a lower flushing water volume seems to result in a higher frequency of double flushing incidents. This also coincides with the survey results, in which approximately one third of the respondents at both sites experienced a dissatisfactory cleaning effect with the saving flush, resulting in a need for a second flush (Table 1; Q3). On the other hand, the frequency of putative double flushes at the ground-floor toilet with an enforced saving flush mode was only slightly higher than for *DualFlushVac* toilet at the same floor (Figure 3). A distinctly higher frequency of double flushing was not observed at the upper floors (Figure 3), although this was expected considering the observed low freshwater supply pressure. Therefore, factors other than the flushing water volume and flushing water supply seem to impact on the occurrence of double flushing incidents, such as principal user habits (e.g., flushing the toilet at the start of each visit regardless of its cleanliness).

Interestingly, 79–91% of the putative double flushes that were registered at the six *DualFlushVac* toilets of the office building occurred in subsequence to a regular flush (Figure 4). This may imply that for those occasions that the saving flush mode is selected, users are satisfied with its cleaning effect. For the residential houses, a significant ($p < 0.01$) more-frequent usage of the saving flush button was registered at the ground floor while no significant ($p = 0.78$) difference was observed between the two floors for the fraction of putative double flushing incidents (Figure 3). This implies that a more frequent usage of saving flush mode does not necessary result in a greater frequency of double flushing incidents. A more detailed statistical analysis of the identified putative double flush incidents (Figure 4 right) partly confirms this hypothesis, by showing a weak, but not significant ($p = 0.19$), indication that double flush incidents actually occur more frequently subsequent to a regular, than a saving, flush, which is in accordance with the findings for the office building. The reason that a regular flush may more frequently result in a dissatisfactory cleaning may be due to the fact that a saving flush is mainly used after urination, which usually contaminates the toilet bowl only to a small extent.

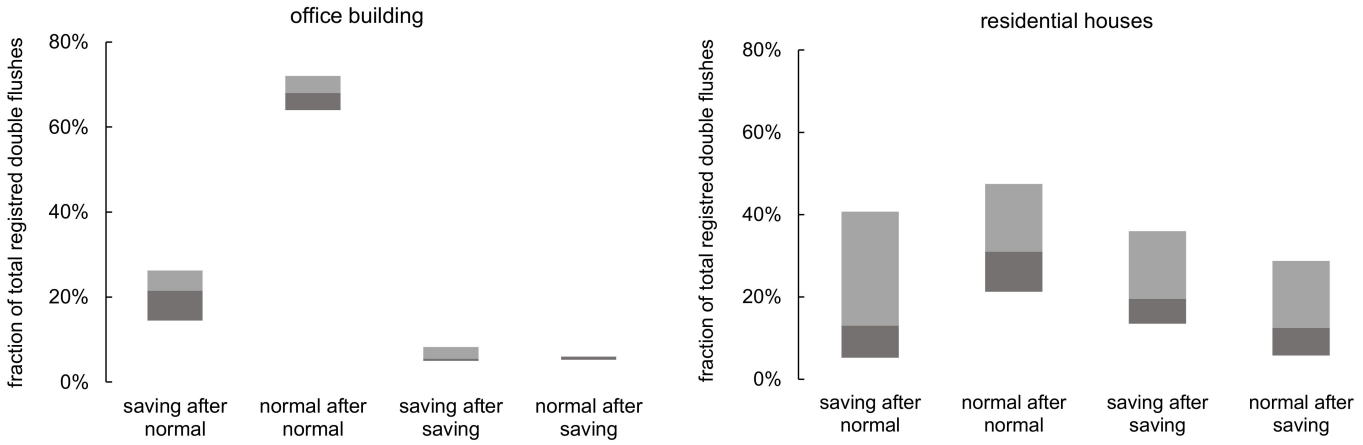

Figure 4. Details on flushing mode (normal, saving) of the identified putative double flushes (defined as a flush occurred upon 180 s to the previous flush at the same toilet) for the office building (right) and residential houses (left). The bars show the variation over respectively, with the intervals between median and first and third quartile.

The data shown in Figure 5 show a decreasing tendency in the usage of the saving flush button over time for the residential houses. This may point to an increasing user dissatisfactory with the cleaning effect of the saving flush mode and more frequent usage of regular flushing mode. The frequency of double flushes on the other hand remained constant over the whole period (Figure 5, right). This means that a less frequent usage of saving flush mode towards the end of the observation period did not result into a concomitant decrease of double flush incidents as it might have been expected if double flushes typically follow a saving flush. This again would be consistent with the above-mentioned weak indication in Figure 4 (right) that double flushing incidents more frequently occur after a regular flush. These double flush incidents that start with a regular flush likely occurred in conjunction with defecation sessions requiring a more in-depth cleaning of the toilet bowl.

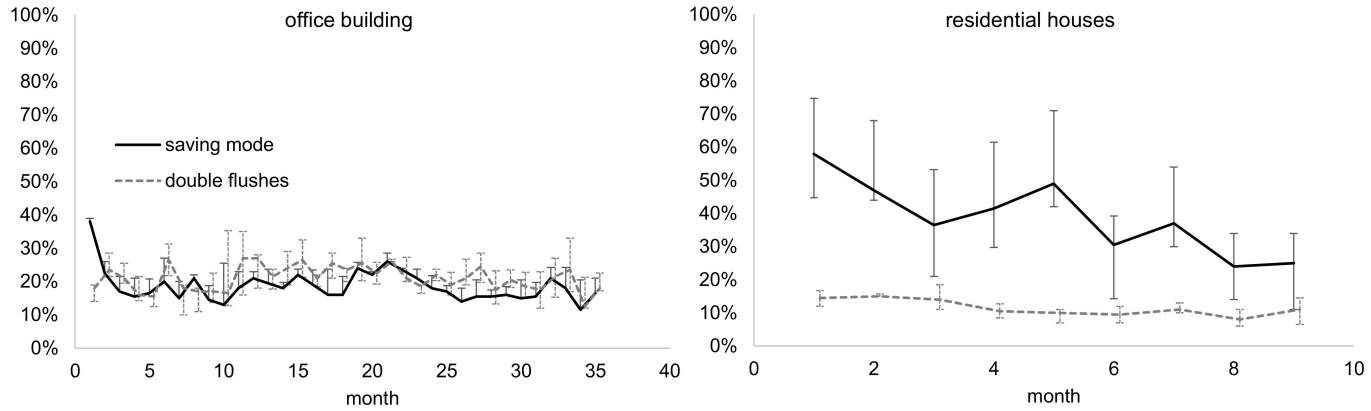

Figure 5. Development over time for fraction of saving mode flushes and fraction of double flushes on the total registered number of flushes. The curves display for each month median values over data gathered from 6 and 10 toilets for the office building and residential houses, respectively. Variation is indicated by the error bars based on the interval between first and third quartile of these monthly data sets.

Considering the results of the multiple-choice survey, for both sites, it seems not unlikely that some people left a toilet in an unsatisfactory state over to the next user (Table 1; Q4), which, again, likely contributes notably to double flushing incidents. In those cases, a subsequent toilet visit likely starts with flushing away the remaining contamination from the precedent visitor and will have again the need for at least one flush at the end of

the session which, again, may be identified as a putative double flush. This means that the flush end of the precedent visit, which is actually performed due to insufficient cleaning, will not represent that flush that was immediately preceding the registered double flush. This, again, relativizes to some extent the above discussed findings that a double flush incident occurs more frequently in subsequence to a regular, rather than a saving, flush, as the insufficiently performing flush at the end of the precedent toilet visit might have been a saving flush. Nevertheless, the flushing volume applied for the *DualFlushVac* toilets seems to be at a critical limit in terms of cleaning efficiency. A further reduction will likely result in more frequent double flushing incidents which, again, would outweigh its water saving effect.

Both log data and multiple-choice survey responses show that quantifying the effective water consumption dual-flush and other types of water saving toilets is far more complex than determining a nominal average flushing water volume for a particular toilet model under lab conditions and multiplying it with an estimated number of flushes per person equivalent. Both factors may vary considerably from site to site. The effective water consumption per flush may deviate considerably from the nominal volumes determined under standard conditions at locations with varying pressure conditions in the freshwater supply. Data gathered about the issue of double flushing show that the number of flushes per person equivalent can vary considerably, depending on the cleaning effect that a single toilet flush is performing and, accordingly, user satisfaction. For dual-flush toilets, as investigated by this study, other factors, such as availability of urinals as well as user awareness for water saving, seem to impact significantly on the usage frequency of the saving flush mode and, thereby, the average water consumption per flush.

Opportunities for Increased Resource Recovery from Toilet Wastewater

The reduced flushing water volume of the *DualFlushVac* toilets results in more concentrated wastewaters which are suitable for the recovery of resources. The concentration of the chemical oxygen demand (COD) and nutrients (nitrogen and phosphorous) is 1.5–2 times higher in the blackwater collected from the *DualFlushVac* toilets as compared to values in the literature (Figure 6). Hence, it can be assumed that 25–50% lower flushing water consumption is achievable with the tested *DualFlushVac* toilet model compared to traditional vacuum toilets. The potential for high rate anaerobic treatment in UASBs of blackwater collected with conventional vacuum toilets has been demonstrated by several studies [11,12]. By doing so, the COD is used for energy production and the nutrients (N and P) are released via the liquid phase to different types of recovery processes that can be connected to the UASB effluent. The treatment of source separated domestic wastewaters with the subsequent recovery and reuse of nutrients in agriculture has been recognized as an alternative to treatment and recovery as opposed to centralized systems [13]. Cunha et al. (2020) have shown that it is possible to produce a fertilizer (Ca-P) from blackwater. Others have observed the formation of struvite directly in blackwater [14]. Provided the appropriate environmental conditions are applied, this is also possible with effluent of an anaerobic treatment. N recovery methods are not widely applied yet, although there are technologies available for N-stripping from digestate (e.g., Baldi et al. 2018 [15]). However, in most cases, the stripping of N is done only at higher concentrations and from solutions that are relatively clean, like UASB effluent [16]. Producing blackwater with higher COD, N and P concentrations is beneficial for all anaerobic treatment and subsequent post treatment for recovery [17]. The energy (methane) produced during anaerobic treatment depends on the COD concentration of the blackwater. Higher COD concentrations allow treatment of the black water at higher temperatures (e.g., 55 °C) which could result in the production of hygienically safe fertilizers [18].

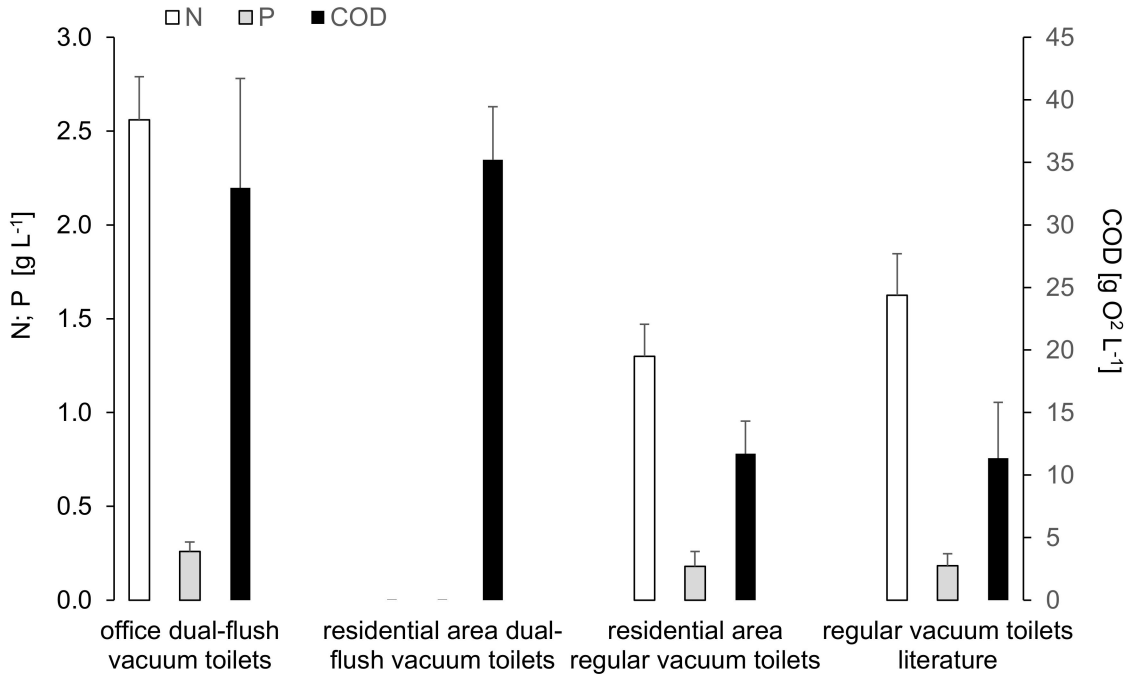

Figure 6. Average concentration range of organic matter and main nutrients in blackwater from the two demo sites with installed dual-flush vacuum toilets compared to blackwater from the former regular vacuum toilets at the residential area and blackwater data from other projects using vacuum toilets in Norway, The Netherlands, and Germany [2]. Error bars are showing the standard deviation.

4. Conclusions

- A 25–50% lower flushing water consumption and, accordingly, 1.5–2 times higher nutrient concentration seems to be achievable with the dual-flush vacuum toilet. For office buildings and public facilities, the effect of a dual flushing feature is less pronounced, especially for men's toilet facilities that provide urinals in addition to toilets.
- For dual-flush toilets, as investigated by this study, other factors, such as the availability of urinals, as well as user awareness for water saving, seem to significantly impact the usage frequency of the saving flush mode and thereby the average water consumption per flush.
- User satisfactory with the toilet cleaning effect is a critical issue that can result in a notable number of double flushing incidents, which, again, may outweigh the effective water saving effect of toilet models with low nominal flushing volume.
- There is a certain lower limit for the flushing volume. A further decrease would likely increase the occurrence of double flushing incidents and lead to a greater tendency for using the regular flushing mode. These trade-offs outweigh any further water saving effect.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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